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TESIS DOCTORAL

Redes Atencionales y Vigilancia Ejecutiva y de Activación

Attentional Networks and Executive and Arousal Vigilance

Doctorando

Fernando Gabriel Luna

Directores:

Juan Lupiáñez Castillo y Elisa Martín-Arévalo

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Chapter I

Introduction

The attentional networks system

A large amount of behavioral, clinical, physiological, and neuroimaging evidence accumulated over several decades motivated Posner and collaborators to propose an integrative model of attention as a system supported by three independent networks (i.e., alerting, orienting, and executive control) with the capacity to interact among them (S. E. Petersen & Posner, 2012; Posner & Dehaene, 1994; Posner & Fan, 2008; Posner & Petersen, 1990). Whereas a deeper description of the neural mechanisms of the attentional networks will be presented further on, the following sections introduce an initial overview of the brain regions and cognitive processes associated for each of the attentional networks.

The orienting network

Initial reviews proposed a posterior network as a circuit mainly comprised by the superior colliculus and the pulvinar nuclei of the thalamus along with the posterior parietal cortex (Posner & Dehaene, 1994; Posner & Petersen, 1990), but further research has concluded that the frontal eye fields and the temporo parietal junction would be also engaged in this network (J Fan, McCandliss, Fossella, Flombaum, & Posner, 2005; Posner, Sheese, Odludaş, & Tang, 2006). Evidence from brain injury studies has assigned a critical role the cholinergic neurotransmitter in the posterior network (Posner, 2012b).

The main activity of this network is to modulate attentional orienting towards spatial sources of the environment to locate potentially relevant stimuli, or to adapt the processing scale to either pay attention to the global aspects or to the details. Note that attentional orienting can be captured either automatically by exogenous or peripheral cues from the context (e.g., in an experimental task, an asterisk in the top of the screen), or voluntarily by endogenous or internal signals (e.g., a predictive central arrow pointing towards the top of the screen; Ruz & Lupiáñez, 2002). To measure the behavioral performance of attentional orienting, experimental paradigms usually present endogenous or exogenous visual cues that predicts either correctly (i.e., valid cues) or incorrectly (i.e., invalid cues) the location of the incoming target stimuli (Posner, 1980, 2014). In general, it is observed that valid cues facilitates attentional orienting with faster reaction time (RT) and more accurate responses than neutral cues, which provide no spatial information, whereas invalid cues hinder performance (Posner, 2014; Ruz & Lupiáñez, 2002).

The executive control network

A second subsystem of the model proposed by Posner and collaborators is an anterior network that mainly connects the anterior cingulate and midline prefrontal cortices (Posner & Dehaene, 1994; Posner & Petersen, 1990). Extended research on the anterior network has led to propose two dissociated brain circuits within this subsystem: (a) a cingulo-opercular network, which comprises orbital and anterior regions of the frontal lobe, the anterior cingulate cortex, and the thalamus; and (b) a frontoparietal network, that connects the dorsolateral prefrontal and the medial cingulate cortices, with the precuneus and regions from the superior parietal lobe (Dosenbach, Fair, Cohen, Schlaggar, & Petersen, 2008; S. E. Petersen & Posner, 2012). At difference with the posterior network, the anterior system seems to be regulated mainly by the dopaminergic neurotransmitter (Posner, 2012b).

The anterior network underlies executive control processes that select relevant information (e.g., a target stimuli) from environment and inhibit the irrelevant one (e.g., the distractors stimuli), with the aim of adapting our behavior to long term goals (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Shenhav, Botvinick, & Cohen, 2013). It is well-known that selection can be driven, and therefore goals achieved, by two different mechanisms: (a) bottom-up or reactive processes, which are guided by the salient physical properties of stimuli (e.g., the color or the shape) that perceptually segregates targets from distractors; and (b) by top-down or proactive mechanisms, which are driven by a goal-directed behavior and pre-meditated plans of actions (Braver, 2012; Kim & Cave, 1999; Notebaert, Gevers, Verbruggen, & Liefooghe, 2006; Shomstein, 2012). One of the widely used methods to assess the executive control network is the Eriksen flanker task, in which distractors interfere with the selection of the target (Eriksen & Eriksen, 1974). The interference effect is reflected as slower and less accurate responses when distractors are incongruent with the target (e.g., when selecting the direction pointed by a central arrow surrounded by opposite direction arrows: <<><<), than when stimuli are congruent (e.g., the same task with the following set of stimuli: >>>>>) (see, e.g., Funes, Lupiáñez, & Humphreys, 2010). No matter how easy is selection depending on physical properties of stimuli, or the previous experience we have with them, executive control can guarantee that the goal is fulfilled as, for example, when naming the ink color in a Stroop task (i.e., the word white written in black) (Botvinick, Cohen, & Carter, 2004).

The alerting network

The third subsystem is the alerting or general activation network, a brain circuit that connects the locus coeruleus with the parietal and prefrontal cortices of the right hemisphere (Posner & Petersen, 1990). This network regulates general arousal by noradrenergic innervations projected from the locus coeruleus; a basal nuclei that produces noradrenaline (S. E. Petersen & Posner, 2012; Posner, 2012b). Although the initial conception of the alerting network was a circuit lateralized to the right hemisphere, further neuroimaging researches have provided additional evidence concerning a relevant role of the left parietal and prefrontal cortices in the moderation of brief shifts of arousal (J Fan et al., 2005).

The alerting network modulates two different states of arousal: (a) the phasic alertness, conceived as a brief increment of arousal necessary for readiness to imminent events; and (b) the tonic alertness or vigilance state, understood as the capacity to sustain attention for extended periods of time (S. E. Petersen & Posner, 2012; Posner & Petersen, 1990). Phasic alertness is usually assessed by presenting anticipatory signals to the response stimuli (Posner, 2008). Experimental research on sensory modalities suggests that auditory signals are more effective to increase phasic alertness than visual stimuli (Fernandez-Duque & Posner, 1997; Kusnir, Chica, Mitsumasu, & Bartolomeo, 2011; A. Petersen, Petersen, Bundesen, Vangkilde, & Habekost, 2017). The phasic alertness effect is observed as faster RT after a warning signal than when stimuli are not anticipated at all (Posner, 2008). Regarding vigilance, an extended review of this concept is necessary for the goals of the current dissertation, and so it will be more deeply discussed in the following section.

The multiple conceptions of vigilance

The classical literature on cognitive and brain research generally use as synonyms the terms of tonic alertness, sustained attention, and vigilance, to denominate the ability of the cognitive system to maintain an optimal level of attention during extended periods of time (Asanowicz & Marzecová, 2017; J Fan, McCandliss, Sommer, Raz, & Posner, 2002; Martella et al., 2014; Posner, 2008, 2012a; Posner & Petersen, 1990; Sarter, Givens, & Bruno, 2001; Thomson, Besner, & Smilek, 2016). Furthermore, even if vigilance is recognized as the most widely used of these terms, there are indeed different accepted conceptions in the literature for this concept. In particular: (a) in the neuropsychological field, vigilance refers to the regular shifts of the arousal levels that are related with the circadian rhythms of the sleep-wake cycle, which can be compromised by brain lesions; (b) in the psychiatric field, it refers to a hypervigilance state of the attentional system for preventing, coping with or anticipating potential dangers or threats, a typical symptom observed in the post-traumatic stress disorder; and (c) in the psychological field, it denotes the ability for sustaining attention over long periods of time on a given task, wherein it is commonly observed a decrement of performance across time on task (Oken, Salinsky, & Elsas, 2006). Although all the different conceptions of vigilance will be relevant to address the proposed goals in the present dissertation, we will begin examining vigilance in the same vein that cognitive psychology has usually analyzed this process, i.e., as the challenging ability to sustain attention over extended periods of time.

The vigilance decrement phenomenon

The initial experimental studies of vigilance can be recovered from the 1940's decade in the context of the II World War (Hancock, 2017). The need of the British Royal Air Force to determine with extreme precision the capacity of radar operators to monitor and detect efficiently the occurrence of critical events during long periods of time, led to require to N.H. Mackworth the development of a behavioral task suitable for measuring the vigilance ability of radar operators (Mackworth, 1948; Scerbo, 1998). The test developed at that time, which is nowadays known as the Mackworth Clock Test (MCT; Mackworth, 1948), consists in watching during two uninterruptedly hours the second's hand of a clock that jumps regularly a single space (i.e., from one second to the next in the clock face) most of the times, but critically, in rare occasions it jumps twice the regular space (i.e., two seconds in the clock face). The participant goal is to detect all the infrequent critical signals (i.e., the double jumps of the second's hand) over the two hours by pressing a specific response key as fast as possible. The key finding reported by Mackworth (1948) was that the ability to correctly detect infrequent critical signals over an extended period of time tends to decrease across time on task.

In the following decades, experimental research concerning vigilance has consistently replicated the original finding of Mackworth (1948), thus further supporting that the vigilance decrement phenomenon reflects the loss of sustain attention in prolonged tasks as a progressive drop in the hits to detect infrequent critical signals, and also as an increment on RT across time on task (Adams, 1987; Hancock, 2017; Scerbo, 1998; See, Howe, Warm, & Dember, 1995;

Thomson et al., 2016). Interestingly, and critically for the goals of the present dissertation, although both the hits on signal detection and the RT of responses have been generally analyzed as part of the same mechanism of the vigilance decrement, it might be probable that these behavioral measures would be indeed reflecting dissociable cognitive components of vigilance. To further address this issue, the next sections review the literature concerning the vigilance decrement either on signal detection tasks, or in specific RT tasks.

The executive vigilance decrement in signal detection tasks

Vigilance has been widely assessed by signal detection tasks like the MCT (Mackworth, 1948) or the Continuous Performance Test (CPT; Conners, 2000), wherein participants must sustain attention over long time periods to detect the occurrence of rare but critical targets. The CPT is a ~14 consecutive minutes task in which participants have to respond permanently to the presentation of any single letter while withholding the response only when a specific letter (i.e., the 'X') appears on the screen (Burton et al., 2010; Conners, 2000). In the same vein, the Sustain Attention to Response Task (SART) has been also proposed as a sensitive measure to assess vigilance performance (Robertson, Manly, Andrade, Baddeley, & Yiend, 1997). In the SART, participants must watch and execute the same response to the continuously presentation of any of the nine digits (i.e., 0 to 9), while inhibiting that response to a particular pre-specified target (e.g., the number 3). The SART has been found as a sensitive task for detecting attentional failures in traumatic brain injury patients by observing a lower hits rate and slower RT in contrast with healthy adults (Chan, 2001; Robertson et al., 1997).

Note that, according to Helton, Kern, & Walker (2009), the SART seems to be a task very similar to go/no-go paradigms, with the particular detail that includes a high frequency of 'go' events (i.e., the no-signal trials wherein participants must execute the expected response). Indeed, for Helton and colleagues, the SART would be an appropriate task to assess both the capacity of response' strategies and a motor component of impulsiveness, two necessary processes to implement an active control of the attentional system for withholding the response in the infrequent events of the task (Helton, 2009; Helton, Head, & Russell, 2011; Helton et al., 2009; Helton, Weil, Middlemiss, & Sawers, 2010).

Regardless the particular design and stimuli differences between the MCT, the CPT, and the SART, the common process is the sustenance of attention for monitoring the occurrence of rare but critical events that must be detected by performing a specific response (or inhibiting it), which is indeed a different response from the one expected in the remaining frequent events. From now on, we will refer to this cognitive ability as the executive component of vigilance (EV), which indeed has been traditionally analyzed by Signal Detection Theory (SDT) metrics (Balakrishnan, 1998; See, Warm, Dember, & Howe, 1997; Stanislaw & Todorov, 1999; Wixted, 2019). From the SDT approach, responses in a EV task can be categorized as: (a) hits, i.e., the correct responses over the infrequent critical targets or the signal events in terms of SDT; (b) misses, i.e., the failures in detecting the infrequent critical signal; (c) false alarms (FA), i.e., the attempts to detect an infrequent target when the stimuli presented is one of the frequent stimuli or noise events in terms of SDT; and (d) correct rejections, i.e., the correct responses to the frequent stimuli or noise events.

Note, however, that misses and correct rejections are not informative as they can be derived from hits and false alarms, if the overall signal presentation rate is known. Nevertheless, and importantly, neither hits nor the FAs alone are fully informative regarding the EV performance. For instance, could we assume that two participants with a hits rate of 90% have the same capacity to detect infrequent signals, if one has a FA rate of 5% and the other one of 50%? Definitely not. In order to analyze performance we need to jointly consider hits and FA, which is what SDT does. Thus, the EV performance is indeed better examined by SDT metrics as the sensitivity and the response bias (Stanislaw & Todorov, 1999). The sensitivity refers to the ability to efficiently discriminate signals from noise events: whereas a higher sensitivity refers to a better discrimination, a lower sensitivity indicates a higher confusion between signal (targets, i.e., infrequent events in vigilance tasks) and noise (non-targets, i.e., frequent events). Instead, the response bias refers to the criterion assumed to detect correctly the infrequent signals but, critically, taking into consideration the costs of committing FA errors: whereas a more liberal response bias is observed in cases wherein participants do not care to commit many FA in order to achieve a high hits rate, a more conservative response bias is found in cases in which it is preferred to detect less infrequent signals but to also commit fewer FA errors (Stanislaw & Todorov, 1999).

Thus, after many years of research addressing EV performance in long experimental tasks, there has been a notable consensus that the typical decrement observed in hits seems to correspond to a progressive drop in sensitivity rather than a shift in the response bias (R. A. Grier et al., 2003; See et al., 1995; Warm, Parasuraman, & Matthews, 2008). However, the widely-reported sensitivity-loss effect has been recently criticized by a review and empirical demonstration conducted by Thomson et al. (2016). The authors stated three main objections to the modern vigilance tasks to assess and analyze the EV decrement: (a) the typical methods to assess EV are generally long, repetitive, and intellectually unchallenging behavioral tasks that are indeed very easy to perform successfully by participants, and as consequence, it is usually observed both a ceiling effect in the hits along with a floor effect in the FA; (b) to observe a probable shift in the response bias towards a more conservative criterion, it is imperatively necessary that the decrement on the hits be accompanied by a similar decrement in the FA, something that is highly unlikely to occur if FA are already at the floor in the first period of the task; and (c) the classic parametric indices usually computed for sensitivity (i.e., d′) and response bias (i.e., β) assume a normal distribution of responses, and therefore these indices are not strictly adequate to analyze the EV performance when the hits are at the ceiling and the FA at the floor, because the scores must be replaced in some way when they are 100% or 0%, respectively (a performance commonly observed across a sample when data is analyzed by periods of time) (Stanislaw & Todorov, 1999).

Therefore, to empirically demonstrate the hypothesis regarding that the EV decrement is best interpreted as an increment in the response bias when FA are not at the floor, Thomson et al. (2016) developed an original EV task with the specific aim to increase the FA rate. Participants completed a signal detection task in which they had to watch permanently noun-words trying to detect the appearance of nouns referring to four-legged creatures (e.g., ‘squirrel’, 10 signal targets per block of trials). Importantly, the remaining 90 frequent events per block included: (a) object nouns (e.g., ‘book’, 80 per block); and (b) non-four-legged creatures (e.g., ‘eagle’, 10 per block), which were categorized as lure trials wherein it was expected to observe a higher FA rate than in the remaining frequent events. Interestingly, when the FA rate was computed only considering the lure trials, it was observed a prominent increment of FA in the first block of trials (i.e., ~33%). Most importantly, as a consequence of the significant decrement across blocks observed in both hits and FA, it was found a progressive increment in the response bias towards a more conservative criterion and no decrement in the sensitivity, thus supporting the hypothesis that when FA are not at floor, the EV decrement is best interpreted as a shift in the response bias (Thomson et al., 2016).

The arousal vigilance decrement in RT tasks

Interestingly, it should be noted that although the vigilance decrement phenomenon has been widely-reported as a progressive drop in hits and also as progressive increment of RT across time on task, indeed the RT is not informative at all regarding the ability to detect infrequent critical targets in the EV component (Thomson et al., 2016). For instance, does a progressive slowness in RT across time on task refers either to a raising difficulty for discriminating signal from noise events, or to a progressive shift towards a more conservative criterion for attempting to commit fewer FA? Moreover, and critically, the aforementioned conception of vigilance as the ability to sustain attention for detecting infrequent critical targets (i.e., the already denominated EV component) seems to be quite different from another behavioral conception of vigilance understood as the capacity to maintain a fast reaction to stimuli from environment, without needing to select a specific response over these stimuli (Lim & Dinges, 2008; Tkachenko & Dinges, 2018).

Taking into account the classic behavioral tasks usually administered to analyze the vigilance decrement, it is important to highlight that in tasks like the Psychomotor Vigilance Test (PVT) vigilance is assessed in a very different way than in typical signal detection tasks like the MCT (Mackworth, 1948), the CPT (Conners, 2000), or the SART (Robertson et al., 1997). In particular, in the PVT, participants must remain vigilant over 10 minutes to stop, as fast as possible and by pressing any available response key, a millisecond down counter that appears at random intervals between 2 to 10 seconds (Lim & Dinges, 2008). From now on, we would refer to the arousal component of vigilance (AV) as the ability for sustaining attention over long time periods to keep a fast reaction to stimuli from environment without selecting a specific response.

Note that with the PVT, the AV decrement is consistently reported as a relevant increment across time on task of RT measures, like the mean or median RT, the variability of RT, and the percentage of lapses (i.e., the responses slower than an established threshold, usually set at 500 milliseconds in the PVT) (Basner & Dinges, 2011; Basner, Mollicone, & Dinges, 2011; Lee, Bardwell, Ancoli-Israel, & Dimsdale, 2010; Lim & Dinges, 2008; Loh, Lamond, Dorrian, Roach, & Dawson, 2004). Importantly, the AV component seems to be closer to the notion of vigilance as the regular shifts of arousal related to the sleep-wake cycle (Oken et al., 2006), and indeed the PVT has been demonstrated as a sensitive task to examine the effects of partial or total sleep deprivation over vigilance performance (Basner & Dinges, 2011; Basner, Rao, Goel, & Dinges, 2013; Lim & Dinges, 2008; Tkachenko & Dinges, 2018). For instance, by administering the PVT in consecutive hours over an extended wakefulness period, it has been found that the percentage of lapses tends to increase considerably as the time progresses (Basner & Dinges, 2011; Lamond et al., 2008).

Further research on the AV decrement has proposed that the RT variability might be considered as the most sensitive measure of the shifts in AV across time on task (for a review, see Tkachenko & Dinges, 2018). Indeed, the changes in the RT variability across time on task has been considered as evidence of two different AV states: (a) 'in the zone', as a period wherein it is commonly observed a more stable performance and therefore, it is more unlikely that attentional failures and lapses occurs; and (b) 'out of the zone', a state wherein it is often observed a high RT variability, and so it is more probable that attentional lapses occurs (Esterman, Noonan, Rosenberg, & Degutis, 2013).

Measuring vigilance nowadays: Can vigilance tasks be administered online?

It must be noted that, traditionally, vigilance has been assessed either inside or outside the lab, but with a particular strong interest of researchers for controlling the experimental conditions in which the behavioral task is administered (Basner et al., 2008; Hancock, 2017; Lamond, Dawson, & Roach, 2005). However, in a recently published study, Claypoole, Neigel, Fraulini, Hancock, & Szalma (2018) raised the issue of whether vigilance tasks could be administered online (p. 1348), opening a debate concerning the feasibility of measuring the vigilance decrement phenomenon with online tasks performed outside the lab. Note that the interest for using online methods to collect large sample sizes has raised importantly in the last years (Sassenberg & Ditrich, 2019), partially motivated by the imperative need of reducing the probability of false positive errors in psychological science (Munafò et al., 2017).

Nevertheless, to date, only three studies have reported using online tasks to assess vigilance performance outside the lab, and in particular for measuring the EV component (Fortenbaugh et al., 2015; Ralph, Thomson, Seli, Carriere, & Smilek, 2015; Sadeh, Dan, & Bar-Haim, 2011; Thomson et al., 2016). To account for this lack of evidence regarding measuring vigilance online, Claypoole et al. (2018) argued that: (a) if researchers have indeed conducted vigilance experiments online but the findings were non-significant, then probably the results remain unpublished, which is an issue strongly observed for psychological and social sciences, known as the 'file drawer' problem (Franco, Malhotra, & Simonovits, 2014; Munafò et al., 2017); (b) in an online session, the experimental conditions cannot be controlled as in the lab, and so there might be unexpected factors that can effectively enhance or impair vigilance functioning across time on task (e.g., it has been demonstrated that mastication helps to mitigate the vigilance decrement, see Miquel, Haddou, & Day, 2019; Morgan, Johnson, & Miles, 2014); and lastly, (c) given that the task would be completed on different devices and environments, the lack of perceptual uniformity in an online experiment (i.e., as a result of, for instance, different screen sizes or luminosity intensities across the sample) might have a relevant – and again, uncontrolled and unexpected – influence on the vigilance performance (Hashimoto, Kumashiro, & Miyake, 2003).

Notwithstanding, and critically, EV was successfully measured outside the lab in the few studies conducted with online tasks (and in the present dissertation; see Chapter 5). In particular, the decrement across time on task was indeed observed with online signal detection tasks, either as a drop in sensitivity (Ralph et al., 2015) or as a progressive increment in the response bias (Thomson et al., 2016). Furthermore, using an online version of the CPT which was performed at participant's home, Sadeh et al. (2011) found that after a night of partial sleep deprivation (i.e., 4 hours of sleep) there was an important reduction in the hits on target detection. Lastly, and most importantly, the relevant increment in the response bias observed by Thomson et al. (2016) with an online signal detection task was replicated then by Claypoole et al. (2018), by administering the task in the typical lab conditions, thus providing further evidence concerning the feasibility of measuring vigilance with online tasks.

The theoretical explanations of the vigilance decrement phenomenon

As above-discussed, the initial empirical demonstrations of the vigilance decrement phenomenon emerged from applied behavioral research in the context of the II World War. Although the lab research conducted by Mackworth was successful in determining the capacity of British Royal Air Force operators to detect the enemies' presence on the radar during extended periods of time, at that time there was no adequate framework accounting for the cognitive mechanisms underlying the vigilance decrement (Hancock, 2017; Mackworth, 1948; Thomson, Besner, & Smilek, 2015). This lack of theory behind for explaining such a widely-replicated phenomenon motivated a large body of empirical research that have proposed and supported different theoretical explanations, like the resource overload and mind wandering accounts, which nevertheless, nowadays are still under debate. Therefore, a large discussion exists in the literature regarding the cognitive mechanisms driving the vigilance decrement across time on task (Thomson, Besner, et al., 2015).

The resources overload model

The most widely accepted account about the vigilance decrement has been developed over the idea that the attentional system works as a limited pool of available resources that are requested, depleted, and replenished, as a function of variables such as time, the physiological levels of arousal, and the external demands from the environment (Kahneman, 1973). From this perspective, the vigilance decrement would correspond to a progressive depletion of the available attentional resources to perform the task at hand, that indeed and critically, would not be successfully replenished in the period of time in which the task is completed (R. A. Grier et al., 2003; Hancock, 2017; Warm et al., 2008). Evidence supporting the critical role of time for replenishing attentional resources arises from the fact that resting while performing the task is an effective countermeasure to mitigate the decrement of performance usually observed across time (Helton & Russell, 2017).

It should be noted that the resources overload model has mainly attempted to account for the EV decrement rather than the AV decrement. Thus, the widely-reported sensitivity-loss effect has been consistently explained from this model as a behavioral pattern of the progressive depletion of attentional resources across time on task (See et al., 1995; Thomson et al., 2016). Importantly, the explanations concerning the resources depletion hypothesis has been partially based on the subjective reports of participants, who state that the typical signal detection vigilance tasks demand a hard mental work and are experienced as a highly stressful (R. A. Grier et al., 2003; Thomson, Besner, et al., 2015; Warm et al., 2008). Further evidence supporting the resources overload model has been reported from studies wherein an increment in the cognitive loads of the task (e.g., performing a dual-cognitive tasks) have led to an even larger decrement (Epling, Russell, & Helton, 2016; Head & Helton, 2014; Helton & Russell, 2011; but see Chapter 4 of the present dissertation for a differnet pattern).

The mind wandering hypothesis

Nevertheless, along the last two decades, an alternative proposal has challenged the accepted conception that the vigilance decrement corresponds to a progressive depletion of the available resources of the attentional system. A critical point of this alternative model is that attentional resources, although used as a metaphoric concept to understand cognitive mechanisms, cannot be just consumed and therefore, entirely eliminated from the attentional system across time on task (Thomson et al., 2016; Thomson, Besner, et al., 2015). The theoretical explanation developed from the mind wandering model is that, as time on task progresses, attentional resources are rather re-directed from the task-relevant-thoughts necessary to complete the external activity at hand, towards internal and irrelevant thoughts that are entirely unrelated to the external activity, i.e., to mind wandering (Smallwood & Schooler, 2006; Stawarczyk & D'Argembeau, 2016; Thomson, Seli, Besner, & Smilek, 2014).

From the mind wandering account, the typical signal detection vigilance tasks, rather than requiring a hard mental work and being experienced as highly stressful (R. A. Grier et al., 2003; Warm et al., 2008), would be indeed conceived as cognitive activities quite repetitive and intellectually unchallenging (Thomson et al., 2016; Thomson, Besner, et al., 2015). Therefore, following this theoretical perspective, the vigilance decrement is interpreted as a loss of the attentional engagement for keeping an adequate performance over an extended period of time, which would be considered as unnecessary to complete such a monotonous and boring activity (Danckert & Merrifield, 2016; Robertson et al., 1997; Thomson, Besner, et al., 2015). Thus, the stress might come from the need to maintain attention on an undemanding task that is judged as not needing attention, and the reduced performance would have its origin on attention disengagement rather than on depletion of attentional resources. This attentional disengagement from the task would be critically related to the emergency of task unrelated thoughts irrelevant to perform the task at hand, which can be, for instance: (a) thoughts about side aspects of the task, like the duration or the level of difficulty of the activity; (b) external distractions provided from the environment or from internal irrelevant stimuli, as the temperature or the noise felt in the room, or the hunger experienced at that moment; and (c) unrelated thoughts dissociated from both the task and external stimuli (Stawarczyk, Majerus, Maj, Van der Linden, & D'Argembeau, 2011). Thus, in contrast with the resources overload model, an increment in the cognitive demands of the task would lead to a higher engagement on the activity performed and therefore, to a reduced vigilance decrement across time on task (Srna, Schrift, & Zauberman, 2018; Thomson, Besner, et al., 2015).

An alternative framework to the classic explanations of the vigilance decrement

Despite the critical differences observed in the predictions derived from the resources overload and mind wandering accounts, it must be noticed that these models seem to effectively account for a wide set of evidence related to the vigilance decrement phenomenon. For instance, although there is a large body of research supporting that attentional resources are depleted with time on task (Warm et al., 2008), several studies has also reported a strong association between the vigilance decrement and the emergency of mind wandering thoughts across time on task (Thomson et al., 2014). Therefore, with the aim of accounting for the evidence derived from both the resources overload (R. A. Grier et al., 2003; Warm et al., 2008) and mind wandering (Smallwood & Schooler, 2006; Stawarczyk et al., 2011) accounts, the resource-control theory of mind wandering has been recently proposed as an alternative framework to explain the vigilance decrement phenomenon (Thomson, Besner, et al., 2015).

The resource-control theory of mind wandering can be understood as a function of the following hypotheses: (a) the amount of attentional resources available is fixed and permanent, and thus the resources cannot be just depleted or eliminated across time on task; (b) mind wandering thoughts are the default state for an individual (Buckner, Andrews-Hanna, & Schacter, 2008; Fortenbaugh, Degutis, & Esterman, 2017; Raichle, 2015), and the emergency of these internal thoughts does consume attentional resources that, otherwise, would be consumed by the cognitive mechanisms necessary to perform an external activity; (c) executive control processes are crucial to shift the default state towards a goal-directed behavior, and therefore to direct attentional resources towards the external activity performed at hand rather than to internal task-unrelated-thoughts; and (d) critically, executive control tends to decrease across time on task, and so the attentional resources (which, as stated before, are a fixed available amount) would be re-directed from the task-relevant-thoughts towards task-unrelated-thoughts, thus increasing the emergency of a mind wandering state (Thomson, Besner, et al., 2015). Although this alternative framework could be a model with a strong potential for accounting a wide set of phenomena consistently reported as related to the vigilance decrement, to date it has only be theoretically developed, not much empirically tested. Thus, empirical evidence supporting its hypotheses is therefore required, especially regarding the role of executive control in sustaining attention and its decrement across time on task.

Measuring attentional and vigilance components simultaneously

The behavioral performance of attentional and vigilance components has been widely assessed separately by experimental tasks such as the cueing paradigm (Posner, 1980), the flanker task (Eriksen & Eriksen, 1974), warning signal paradigms (Miller, Franz, & Ulrich, 1999), the MCT (Mackworth, 1948), or the PVT (Lim & Dinges, 2008). However, along the last two decades, there has been a considerable and raising interest in combining experimental tasks to better understand the underlying independence and interaction of the cognitive components of the attentional networks system. In other words, as proposed recently by Tkachenko & Dinges (2018), "the development and validation of additional rigorous behavioral tasks capable of dissociating the different aspects of attention across varying levels of cognitive demand is imperative to understanding the relationship between the brain and behavior" (p. 44). Thus, in the following sections, we review the advantages and limitations of behavioral tasks that have been used to provide, within a single session, an independent measure of several attentional and vigilance components.

The Attentional Networks Test

With the aim of simultaneously assessing the functioning of the classic attentional networks components (i.e., phasic alertness, orienting, and executive control), experimental tasks such as the Attentional Networks Test (ANT; Fan et al., 2002) and its further variations (Callejas, Lupiáñez, & Tudela, 2004; J Fan et al., 2009; Funes & Lupiáñez, 2003; Greene et al., 2008; Rueda et al., 2004) have been developed. The ANT is a widely-used task that combines a cueing RT paradigm (Posner, 1980) with an adapted version of the flanker task (Eriksen & Eriksen, 1974). In the ANT, participants have to respond to the direction pointed by the target (i.e., a central arrow), which is surrounded by distracting stimuli that can be either congruent (i.e., arrows pointing to the same direction than the target), incongruent (i.e., arrows pointing to the opposite direction), or neutral (i.e., non-directional lines surrounding the target). The target and distractors stimuli are preceded by either: (a) a spatial informative cue, which indicates the correct location (i.e., above or below the fixation point) wherein the target and distractors will appear in 100% of the trials; (b) a central cue, which is not informative regarding the spatial location of the target; (c) a double cue, which anticipates the response stimuli appearance without providing specific information regarding the target location; or (d) no cue at all.

To analyze the efficiency of the attentional networks functioning, Fan et al. (2002) proposed three independent scores that are computed by subtracting average data between specific conditions of the ANT: (a) the phasic alerting score, as the difference between the no cue and the double cue condition; (b) the orienting score, as the difference between the central cue and the spatial cue condition; and (c) the executive control score, as the difference between the incongruent and the congruent condition. Importantly, Fan et al. (2002) reported non-significant correlations between the attentional networks scores, providing therefore further evidence concerning the independency of the attentional networks proposed by Posner & Petersen (1990).

The Attentional Networks Test for Interactions

Later on, and following the need to assess both the independence and the modulations among the classic attentional components within a single session, Callejas et al. (2004)

modified the experimental design of the ANT and developed the ANT for Interactions (ANTI). In particular, in the ANTI task: (a) the predictive cueing paradigm was replaced by a non-predictive cueing paradigm, which is indeed more sensitive to assess attentional orienting by presenting visual cues that are not 100% predictive of the spatial location of target stimuli; instead, they are either presented at the same (i.e., valid condition; 1/3 of times), or the opposite location (i.e., invalid condition; 1/3 of times), or are not presented at all (i.e., no cue condition; 1/3 of times); (b) the stimuli for measuring phasic alertness was dissociated for the visual cue used for attentional orienting, and therefore replaced by an auditory warning signal that is indeed more effective than a double visual cue to increase alertness briefly (Fernandez-Duque & Posner, 1997); and (c) the neutral flanker condition for target and distractors was suppressed in order to simplify the task, as it was not specifically useful for assessing the functioning of any of the attentional networks (Callejas et al., 2004).

Thus, with the ANTI task, the executive control score is computed as in the ANT, whereas the orienting score is obtained as the difference between the invalid and the valid conditions, thus measuring exogenous or rather involuntary spatial orienting, whereas the phasic alertness score is indexed as the difference between the no tone and the tone condition (Callejas, Lupiáñez, Funes, & Tudela, 2005; Callejas et al., 2004). Furthermore, and most importantly, a clear a replicable pattern of interactions among the attentional networks is successfully observed with the ANTI. In particular: (a) phasic alertness reduces the efficiency of executive control to select the target in the incongruent condition (i.e., a larger congruency effect is observed when the tone is presented); (b) executive control is improved (i.e., congruency is reduced) by valid in contrast to invalid cues; and (c) phasic alertness accelerates attentional orienting functioning under the warning signal effect (i.e., a larger alertness effect is observed at the cued than at the uncued location; Callejas et al., 2005, 2004).

The Attentional Networks Test for Interactions and Vigilance

Interestingly, it should be noted that although the ANT and the ANTI are effective for measuring the classic attentional components simultaneously, none of these tasks provide a direct and independent measure of vigilance. Indeed, several studies have proposed some indirect vigilance scores to be computed with the ANT or ANTI tasks, like the overall RT, or the RT difference between the last and the first experimental block – which might be informative regarding the vigilance shifts across time on task – (Callejas et al., 2005; Ishigami & Klein, 2010). Similarly, the overall increase in RT observed in some populations has been interpreted as reduced vigilance (Miró et al., 2011; Miró, Martínez, Sánchez, Prados, & Lupiáñez, 2014). However, variables other than changes in vigilance might be the cause of changes in overall RT or differences in RT between the first and last block (for example, practice). Thus, to overcome this limitation Roca and colleagues developed the ANT for Interactions and Vigilance (ANTI-V) task, by modifying the ANTI task to include an independent and direct measure of vigilance, in particular the EV component (Roca, Castro, López-Ramón, & Lupiáñez, 2011).

Thus, in the ANTI-V, participants have to perform in the largest proportion of trials (i.e., 75%) the typical ANTI task of Callejas et al. (2004). Additionally, and to complete correctly the remaining 25% of trials, participants have to stay vigilant all time (i.e., all the experimental blocks without pause) to detect an infrequent critical signal (i.e., a displacement of the target from its central position, either leftwards or rightwards), ignoring in these cases the direction pointed by the target (Roca et al., 2011). The design of the ANTI-V task is adequate to analyze the vigilance performance with SDT, in particular: (a) the hits are computed as the correct detection of the infrequent target displacement; and (b) the FA are computed as the incorrect detection of the target displacement when in fact the critical displacement is not present, i.e., on the more frequent 75% of ANTI trials.

Nevertheless, despite the ANTI-V is an effective task to analyze the EV performance by SDT metrics, and has indeed proven to be effective in measuring the vigilance loss concomitant with sleep deprivation (Roca et al., 2012), several issues have been observed concerning the assessment of vigilance in this task. First of all, the vigilance decrement phenomenon was not reported in the experimental studies conducted with the ANTI-V (Bukowski, Asanowicz, Marzecová, & Lupiáñez, 2015; Casagrande et al., 2017; Martella et al., 2014; Morales, Padilla, Gómez-Ariza, & Bajo, 2015; Roca, Crundall, Moreno-Ríos, Castro, & Lupiáñez, 2013; Roca, Lupiáñez, López-Ramón, & Castro, 2013). In effect, the only evidence regarding a shift of vigilance across time on task was reported as a decrement in the sensitivity after ~26 hours of sleep deprivation in the above mentioned study (Roca et al., 2012). However, even in this study no vigilance decrement across blocks of trials was observed in a single session with the task. Furthermore, and also critically, the infrequent signal seems to be quite challenging to be detected, even for healthy adults and therefore surely would extremely challenging for clinical participants. In the above-cited studies, the hits rate ranged between 45% and 60%, and moreover, participants assumed a very conservative response criterion for signal detection (e.g., an overall β index equal or higher than 7.5). In addition, the task seems also to be even more challenging for measuring vigilance in older adults, as reported in a study wherein about 44% of the sample had to be excluded due to an extremely low performance (Moratal, Huertas Olmedo, & Lupiáñez, 2015). Therefore, the goal of the present dissertation of developing a suitable task to measure the functioning of the three attentional networks and the two components of vigilance (see Chapter 2) seems to be highly necessary.

The reliability of the Attentional Networks Test and its variations

Although the different versions of the ANT have been widely-used to assess the functioning of the attentional networks, the reliability of the attentional scores computed with these tasks has been analyzed only in a few set of studies[1] (J Fan et al., 2002; J Fan, Wu, Fossella, & Posner, 2001; Ishigami & Klein, 2010; MacLeod et al., 2010; Roca, García-Fernández, Castro, & Lupiáñez, 2018). In particular, Fan et al. (2002) analyzed the test-retest reliability of the attentional networks scores in a sample of 40 participants, finding a moderate reliability for phasic alertness (.52) and orienting (.61) scores, but a relative high reliability for executive control (.77). A similar pattern was previously observed by Fan et al. (2001), also by test-retest correlations: whereas the highest reliability was found for executive control (.81), low reliabilities were reported for phasic alertness and orienting (.36 and .41, respectively).

Later on, the analysis of the split-half reliability of the ANT supported previous evidence showing that executive control is the most reliable measure of the classic attentional components (MacLeod et al., 2010). In the study conducted by MacLeod et al. (2010), 10,000 of split-half correlations were computed from a sample of 1129 participants, and the reliabilities scores extrapolated from the Spearman-Brown prophecy formula confirmed a high reliability for executive control (.81), and moderate to low reliabilities for orienting (.58) and phasic alertness (.38).

Interestingly, Ishigami & Klein (2010) compared the reliability of the ANT and the ANTI by assessing in both tasks a small sample (N = 10) but in 10 consecutive sessions. The test-retest reliability for sessions 1 and 2 showed a smaller reliability for executive control in the ANTI (.48) than in the ANT (.86), but higher reliabilities for orienting and phasic alertness in the ANTI (.77 and .64) than in the ANT (.57 and -.02, respectively). However, when the reliability was computed by the split-half method including data from the 10 experimental sessions, it was found: (a) the ANT (.89) and the ANTI (.93) showed a similar reliability for

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[1] For the sake of simplicity, and also taking into account that in general the reliability is much higher for RT than for errors data (Ishigami & Klein, 2010; MacLeod et al., 2010; Roca et al., 2018), the reliability scores reported in this section are only considering RT measures.

executive control; and (b) the orienting and phasic alertness scores were more reliable when assessed with the ANTI (.81 and .98, respectively) than with the ANT (.65 and .80, respectively; Ishigami & Klein, 2010). Taking all these results into account, the study of Ishigami & Klein (2010) provides further evidence that the assessment of phasic alertness and orienting is more reliable with the ANTI than with the ANT, as previously proposed by Callejas et al. (2004).

Regarding the ANTI-V, recently Roca et al. (2018) used a method similar to that of MacLeod et al. (2010; i.e., 10,000 of split-half correlations) to compute the split-half reliabity for the classic attentional components and the SDT metrics of EV in a study with a relative large sample size (*N* = 226). For the classic attentional components, the Spearman-Brown prophecy formula correlations confirmed the pattern of data usually observed with the ANT and the ANTI tasks: executive control showed the highest reliability (.66) in contrast with phasic alertness (.25) and orienting (.34). Most importantly, all the EV measures showed a relative strong reliability, which was higher for hits (.91) and FA (.93) than for the parametric indices of sensitivity (i.e., d′ = .79) and response bias (i.e., β = .71). A similar method is used in the present dissertation (see Chaprter 5) to compute the split-half reliability of the differnet measures of the new task developed in the current work, the ANTI-Vea task.

The neural mechanisms underlying attentional and vigilance components

As previously discussed, the attentional networks model proposes a wide set of brain circuits that modulates the attentional and vigilance processes (S. E. Petersen & Posner, 2012; Posner & Petersen, 1990). With the aim of determining and dissociating the brain regions underlying each of the three attentional networks, there has been a considerable and raising interest in conducting studies that associate the performance observed with behavioral tasks suitable to assess attentional and/or vigilance components, with neuroimaging techniques that are useful to analyze the functional or structural brain circuits underlying these cognitive processes (Posner, 2012b; Posner et al., 2006). Although there is an accepted agreement in the functional mechanisms of the classic attentional components (S. E. Petersen & Posner, 2012), there is a scarce consensus on the structural connectivity underlying the attentional networks (Posner, 2012b; Posner et al., 2006). Therefore, and critically, further evidence from studies combining behavioral and neuroimaging methods is imperatively necessary to better dissociate cognitive processes in general, and of particular interest for the present dissertation, to better understand both the EV and AV in particular.

Brain activity related to attentional and vigilance components

Evidence obtained by functional neuroimaging techniques has supported the proposal that the classic attentional components are related to dissociated brain activity (Posner, 2012b; Posner et al., 2006). For instance, in a study wherein participants performed the ANT at the same time they were being scanned with functional Magnetic Resonance Imaging, an increment of brain activity was found: (a) in the thalamic nuclei along with the prefrontal and parietal cortices, in particular with higher activity in the left hemisphere for the phasic alertness functioning; (b) in the posterior parietal region and the frontal eye fields for the orienting network; and (c) in the anterior cingulate and parietal cortices for the executive control network (J Fan et al., 2005).

However, regarding vigilance, there seems to be a scarce consensus about whether there are indeed differential brain mechanisms involved in EV and AV. While some studies have proposed separated mechanisms between the arousal levels of attention or ‘intrinsic alertness’, and the behavioral components of vigilance that would be necessary to detect infrequent critical signals in long time periods (Langner & Eickhoff, 2013; Sarter et al., 2001; Sturm & Willmes, 2001), others have indeed reported overlapped brain activity for EV and AV. For instance, an increased activity in the default mode network (i.e., a circuit of medial and posterior regions strongly linked to the cognitive functioning in resting-state) has been associated with both: (a) the AV component, when performing the PVT task after 36 hours of total sleep deprivation (Drummond et al., 2005); and (b) the EV component, when performing a typical signal detection task (Danckert & Merrifield, 2016).

However, in general, the vigilance decrement phenomenon has been widely associated rather with changes in the electrical cortical rhythms (Clayton, Yeung, & Cohen Kadosh, 2015). In particular, an increment in the alpha band power has been consistently reported during psychophysiological states of decreased alertness, as sleep or mental fatigue (Oken et al., 2006). Regarding the EV component, the decrement observed in a signal detection task was found in association with a progressive increment in lower-alpha frequencies (7.5-10 Hz) in the parietal cortex; an effect that was found as marginal in upper-alpha frequencies (10-12.5 Hz) (Boksem, Meijman, & Lorist, 2005). In contrast, the decrement observed in AV with the PVT during 24 hours of total sleep deprivation, was strongly associated with a progressive increment of delta (2-4 Hz) and theta (4-8 Hz) frequencies (Hoedlmoser et al., 2011).

Moderating effects of transcranial electrical stimulation on the attentional and vigilance components

Recently, the growing interesting in using transcranial electrical stimulation to modulate behavioral performance has provided another strong source of empirical evidence for understanding the critical role of brain circuits supporting attentional and vigilance components (Hurley & Machado, 2017). In particular, transcranial direct current stimulation (tDCS) consists in the delivery of a small (i.e., between 0.1 and 2.0 mA) intensity of anodal (i.e., positive current) or cathodal (i.e., negative current) stimulation over a target region during a period of time usually no longer than ~30 min, to produce a considerable shift in neurons excitability (Fertonani & Miniussi, 2017). Importantly, although different moderating effects of tDCS over attentional and vigilance performance have been observed, the evidence reported is still insufficient and inconsistent (Coffman, Clark, & Parasuraman, 2014; Reteig, Talsma, van Schouwenburg, & Slagter, 2017).

In general, the effects of tDCS over attentional performance have been addressed by using offline stimulation protocols, in which tDCS is administered at rest and the behavioral task is completed afterwards (Coffman et al., 2014; Reteig et al., 2017). However, it should be noted that these offline stimulation protocols might be examining different neural mechanisms than online ones, wherein tDCS is administered at the same time than the behavioral task is performed. Thus, whereas the former seems to account for the long-lasting effects of stimulation related to neuroplasticity mechanisms, the later might be examining the acute effects of neurons excitability during behavioral assessment (Fertonani & Miniussi, 2017; Yavari, Jamil, Mosayebi Samani, Vidor, & Nitsche, 2017).

In particular, the effects of anodal tDCS over the classic attentional components measured with the ANT were addressed with offline stimulation protocols, and have shown either positive, contradictory, or null moderating effects. For instance: (a) 1.5 mA of tDCS during ~20 min over the right posterior parietal cortex significantly improved (Lo, van Donkelaar, & Chou, 2019) or showed partial effects (Roy, Sparing, Fink, & Hesse, 2015) in the orienting network; (b) improvements on phasic alertness were observed only with 2.0 mA of tDCS during ~30 min over the right prefrontal cortex (Coffman, Trumbo, & Clark, 2012); and (c) no modulations over the executive control network were found by tDCS over right posterior parietal cortex (Lo et al., 2019; Roy et al., 2015), right prefrontal cortex (Coffman et al., 2012), or both left posterior parietal cortex and dorsolateral prefrontal cortex (Roy et al., 2015).

Regarding vigilance, the evidence concerning the effects of anodal tDCS over EV is both scarce and inconsistent (Jacoby & Lavidor, 2018; McIntire, McKinley, Nelson, & Goodyear, 2017; J. T. Nelson, McKinley, Golob, Warm, & Parasuraman, 2014; Roe et al., 2016). For instance, whereas it was found that 1.0 mA of 10 min online tDCS over the left dorsolateral prefrontal cortex effectively helps to sustain the hits rate across time in a signal detection task (J. T. Nelson et al., 2014), null effects of tDCS over the performance in a CPT like task were found by delivering offline 1.8 mA during ~20 min in both the left and right dorsolateral prefrontal cortex (Jacoby & Lavidor, 2018). In contrast, for AV, it was reported that after 24 hours of sleep deprivation, 2.0 mA tDCS during ~30 over the prefrontal cortex min facilitated fast RT on the PVT in the following six hours, but did not reduce the percentage of lapses (i.e., responses slower than 500 ms) (McIntire, McKinley, Goodyear, & Nelson, 2014). Taken all together, although the literature seems to support tDCS as an effective tool to moderate attentional and vigilance components performance, further research is imperatively necessary to better clarify the specific effects of tDCS over the brain circuits underlying the attentional networks components, which clearly justify the investigation presented in Chapter 4 of the present dissertation.

The structural connectivity underlying attentional and vigilance components

Although there is a large amount of research supporting differential brain activity for the attentional and vigilance components, there is much less evidence and consensus concerning the structural connectivity underlying attentional networks (Posner, 2012b). To determine the structural organization of the attentional system, there has been a considerable interest in analyzing the connectivity of white matter tracts underlying the attentional networks by the use of Diffusion Weighted Imaging (DWI; Jones & Leemans, 2011; Posner, 2012b; Posner et al., 2006). An often used approach to understand the links between white matter tracts connectivity and cognitive functioning is to perform virtual *in vivo* dissections of brain fasciculus of interest (Catani & Thiebaut de Schotten, 2008), and then to offline correlate the indices of white matter connectivity with performance scores computed from behavioral tasks (Posner et al., 2006).

Following the above-mentioned methodological approach, it has been reported positive and independent correlations between the attentional networks scores computed with the ANT and the structural connectivity of specific white matter tracts. In particular, significant correlations between: (a) the phasic alertness score with the posterior limb of the internal capsule, (b) the orienting score with the splenium of the corpus callosum, and (c) the executive control score with the anterior corona (Niogi, Mukherjee, Ghajar, & McCandliss, 2010). However, note that executive control processes were also associated with the connectivity of the left dorsolateral prefrontal caudate tracts (Chiang, Chen, Lo, Tsen, & Gau, 2015). In addition, and also in controversy with the findings reported by Niogi et al. (2010), it was proposed that the mechanisms of attentional orienting would be related to a visuo-spatial network lateralized to the brain hemisphere that is supported by three branches of the superior longitudinal fasciculus (SLF). In particular: (a) the voluntary orienting of spatial attention towards target stimuli would be linked to the SLF I, a white matter tract that connects dorsal prefrontal and posterior parietal regions; and (b) the automatic capture of spatial cues would be related to the SLF III, which connects ventral regions of the prefrontal lobe with posterior parietal cortices (Thiebaut de Schotten et al., 2011).

Regarding EV, it has been found that the sensitivity to detect infrequent critical targets across time on task in the CPT is positively associated with the connectivity of the cingulate fasciculus (Takahashi et al., 2010). Nevertheless, further research has also supported that EV would be related to the connectivity of right dorsolateral prefrontal tracts (Chiang et al., 2015). For AV, in contrast, it was observed that the higher connectivity of the genu of the corpus callosum along with others ascending and longitudinal white matter pathways, the higher the performance in the PVT after 24 hours of total sleep deprivation (Rocklage, Williams, Pacheco, & Schnyer, 2009).

Chapter II

Objectives and Overview of the Research

The present dissertation is frame-worked on the basis of the three classical main lines of research on attention and vigilance: (a) the conception of attention as a system integrated by three relatively independent cognitive and brain networks (S. E. Petersen & Posner, 2012; Posner & Petersen, 1990); (b) the vigilance decrement phenomenon, which is often reported as a loss in the ability to detect infrequent critical signals, but also as a progressive slowness in the speed of responses (Lim & Dinges, 2008; See et al., 1995); and (c) the conceptual and methodological diversity on the study of vigilance in the experimental cognitive and brain research (Basner & Dinges, 2011; Mackworth, 1948; Robertson et al., 1997). An integrative and extended conceptual review of these lines of research motivated us to propose a general aim, more clearly detailed in four specific objectives for the present dissertation[2].

Our general aim was to establish a theoretical and empirical dissociation of vigilance in two components (executive – EV – and arousal – AV – vigilance) as two independent mechanisms of the attentional networks system, and to empirically investigate the conceptual dissociation at the behavioral and neural level. This general aim was addressed by several conceptual and empirical analyses conducted either in the Introduction (Chapter 1), the five experimental series (i.e., Chapters 3 to 7), and the General Discussion (Chapter 8) of the present dissertation. Note that, critically, this general aim was driven by the conceptual and methodological diversity observed in the study of vigilance in cognitive and brain research. Thus, to systematically address both a theoretical and empirical analysis of the components of vigilance along the present dissertation, we developed the general aim through four specific objectives:

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[2] Note that every Experimental Series of the present dissertation consists of a research study that has either been published (Experimental Series 1: Luna, Marino, Roca, & Lupiáñez, 2018), submitted for publication (Experimental Series 2: Luna, Barttfeld, Martín-Arévalo, & Lupiáñez, 2019), or is in preparation for publication (Experimental Series 3: Luna, Roca, Martín-Arévalo, & Lupiáñez, 2019; Experimental Series 4: Luna, Román-Caballero, Barttfeld, Lupiáñez, & Martín-Arévalo, 2019; Experimental Series 5: Luna, Lupiáñez, & Martín-Arévalo, 2019). Therefore, there might be certain overlap in the Introduction and General Discussion across Experimental Series.

1. To conduct a conceptual review of the literature regarding the multiple conceptions of vigilance, to consequently propose a theoretical distinction between EV and AV, characterizing the two components as theoretically distinct mechanisms.
2. To develop the ANTI-Vea as an effective behavioral task for measuring, at the same time, the EV and AV decrement across time on task within the context of the attentional networks system.
3. To develop the ANTI-Vea task as a suitable tool to assess attentional and vigilance components through an online free website easy to use outside the lab.
4. To examine the neural mechanisms of the attentional networks system underlying the attentional and vigilance components.

The first specific objective was mainly addressed in the Introduction (Chapter 1) and General Discussion (Chapter 8), but also partially across the literature review conducted in each experimental series (Chapters 3 to 7). To this end, we examined the controversial use of vigilance as a multiple concept to denominate different mechanisms of the attentional networks system (Langner & Eickhoff, 2013; Oken et al., 2006; Sarter et al., 2001). Furthermore, and regarding a behavioral analysis of vigilance, we observed that whereas a large tradition of experimental research has addressed vigilance as the ability to sustain attention over long time periods for detecting infrequent critical signals (Conners, 2000; Mackworth, 1948; Robertson et al., 1997), there is another body of literature that refers to vigilance as the capacity to keep a fast reaction without implementing a specific response over stimuli from the environment (Basner & Dinges, 2011; Lim & Dinges, 2008; see also the Introduction in Experimental Series 1, for an extensive review). Therefore, we proposed a specific denomination of vigilance components to properly address the behavioral patterns and neural mechanisms of each component, in short: the EV, as a cognitive ability for monitoring and detecting infrequent events over extended periods of time, and the AV, as the capacity to sustain a fast reaction across time on task without implementing much control over responses.

The second specific objective consisted in developing a new version of the ANT, the Attentional Networks Test for Interactions and Vigilance – executive and arousal vigilance components (ANTI-Vea), as a suitable task to assess the independence and interactions of the classic attentional components, along with the EV and AV decrement across time on task. Note that this objective was addressed across Experimental Series 1 to 3 (i.e., Chapters 3 to 5) in particular. Importantly, we expected the ANTI-Vea task could be an adequate method to address a potential empirical dissociation between the EV and AV components, and therefore to contribute for achieving the general aim of the present dissertation. Thus, in Experimental Series 1, we first aimed at solving some issues, like the low hits rate and no vigilance decrement previously reported with a previous version (ANTI-V) when measuring EV along with the classic attentional components (Roca et al., 2011). Then, across Experimental Series 1 and 2 (replicating and extending the findings of Experimental Series 1), we examined whether the AV decrement can be independently assessed when measuring at the same time the classic attentional components and EV (Lim & Dinges, 2008). Furthermore, and as part of both the second and the third specific objective of the present dissertation (see below), in Experimental Series 3 we analyzed the split-half reliability of the performance scores obtained for phasic alertness, orienting, and executive control, and both the EV and AV measures (Ishigami & Klein, 2010; MacLeod et al., 2010; Roca et al., 2018).

In addition, in Experimental Series 2 we examined whether the ANTI-Vea is a more suitable method to disentangle the cognitive mechanisms underlying the EV decrement than the traditional single, repetitive, and intellectually unchallenging signal detection tasks like the MCT or the SART (Mackworth, 1948; Robertson et al., 1997; Thomson et al., 2016; Thomson, Besner, et al., 2015). Thus, we designed a novel analytical method to compute the FA rate in the ANTI-Vea for testing the hypothesis recently developed by Thomson et al. (2016), which predicts that if FA are not at floor levels, then the EV decrement is best interpreted as an increment in the response bias rather than as a loss in sensitivity. Furthermore, and also in Experimental Series 2, we used the ANTI-Vea to analyze whether the existing theoretical models of vigilance (i.e., resources overload and mind wandering) are adequate frameworks to account for the vigilance decrement phenomenon (Smallwood & Schooler, 2006; Warm et al., 2008). Therefore, to address all the above-mentioned issues, in Experimental Series 2 we examined the EV and AV performance across a wide set of cognitive loads (Tkachenko & Dinges, 2018), while also analyzing the self-reported levels of mental and physical fatigue after performing a simple, dual, or triple cognitive task.

The third specific objective was achieved by developing an online version of the ANTI-Vea that is easy to be administered outside the lab through an open website publicly available (https://www.ugr.es/~neurocog/Sitio_web/ANTI/). This objective was specifically addressed in the Experimental Series 3 (Chapter 5), wherein a large sample size (*N* = 617) was assessed either with the standard ANTI-Vea (i.e., performed in the lab under the typical experimental conditions) or the online ANTI-Vea (i.e., completed outside the lab through the open website). In addition, to further examine the feasibility of the online ANTI-Vea to assess attentional and vigilance components, we computed the split-half reliability of the performance scores obtained with this version of the task for phasic alertness, orienting, and executive control, and both the EV and AV measures, and compared them to the ones obtained with the standard ANTI-Vea (Ishigami & Klein, 2010; MacLeod et al., 2010; Roca et al., 2018). Importantly, we consider the online ANTI-Vea could be a useful tool for researchers interested in measuring attentional and vigilance components in applied/clinical contexts, and also for researchers looking to accumulate large sample sizes with less time and economic resources.

Finally, the fourth specific objective aimed at examining the brain circuits underlying human attentional networks, with a particular interest in dissociating distinct neural mechanisms for the EV and AV components. This objective was developed along Experimental

Series 4 (Chapter 6) and 5 (Chapter 7). In particular, in the Experimental Series 4, with the aim to bring clarity regarding the specific effects of anodal tDCS over attentional and vigilance components (Coffman et al., 2014; Jacoby & Lavidor, 2018; McIntire et al., 2014; Roy et al., 2015), we performed a tDCS study wherein anodal current stimulation was delivered over two core regions of the attentional networks system (i.e., the right prefrontal and posterior parietal cortices) while participants performed the ANTI-Vea task. In the Experimental Series 5, we examined the structural white matter connectivity underlying attentional and vigilance performance (Chiang et al., 2015; Niogi et al., 2010; Takahashi et al., 2010; Thiebaut de Schotten et al., 2011).

Note that in both Experimental Series 4 and 5, we importantly improved the methodological approaches for addressing the neural mechanisms underlying human attentional networks in contrasts to previous works on this field. Thus, in Experimental Series 4: (a) we used a High Definition-tDCS approach, which increases the precision over the stimulation region than standard tDCS (Kuo et al., 2013); (b) we administered online rather than offline stimulation, to examine the acute effects of neurons excitability during behavioral assessment (Fertonani & Miniussi, 2017); and (c) we analyzed alpha power shifts across time on task at the baseline and post stimulation periods, to further dissociate the changes in electrical cortical rhythms regarding the EV and AV decrement (Clayton et al., 2015). Lastly, in Experimental Series 5, to analyze white matter connectivity in multiple fibers regions, we reconstructed tractographies with the spherical deconvolution approach (Alexander, 2005; Tournier, Calamante, Gadian, & Connelly, 2004), and used a much sensitive index of white matter connectivity (i.e., the hindrance modulated orientational anisotropy) than the one usually reported (i.e., the fractional anisotropy) (Dell’Acqua, Simmons, Williams, & Catani, 2013).

Finally, in the General Discussion (Chapter 8), we discuss the main contributions of the present dissertation to examine how the general aim and specific objectives proposed here have been accomplished. Thus, we summarize the main findings of the present work, and discuss its theoretical and empirical impact to consider the EV and AV components as two dissociated mechanisms of the attentional networks system. Lastly, we introduce some future lines of research that may be considered for developing theoretical models more adequate to explain the vigilance decrement phenomenon, and to further determine the neural mechanisms underlying the EV and AV components with a potential use in clinical and applied contexts.

Chapter III

Experimental Series 1

Executive and arousal vigilance decrement in the context of the attentional networks: The ANTI-Vea task.

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Abstract

Background: Vigilance is generally understood as the ability to detect infrequent critical events through long time periods. In tasks like the Sustained Attention to Response Task (SART), participants tend to detect fewer events across time, a phenomenon known as "vigilance decrement". However, vigilance might also involve sustaining a tonic arousal level. In the Psychomotor Vigilance Test (PVT), the vigilance decrement corresponds to an increment across time in both mean and variability of reaction time.

New Method: The present study aimed to develop a single task –Attentional Networks Test for Interactions and Vigilance – executive and arousal components (ANTI-Vea)– to simultaneously assess both components of vigilance (i.e., the executive vigilance as in the SART, and the arousal vigilance as in the PVT), while measuring the classic attentional functions (phasic alertness, orienting, and executive control).

Results: In Experiment #1, the executive vigilance decrement was found as an increment in response bias. In Experiment #2, this result was replicated, and the arousal vigilance decrement was simultaneously observed as an increment in reaction time.

Comparison with Existing Method: The ANTI-Vea solves some issues observed in the previous ANTI-V task with the executive vigilance measure (e.g., a low hit rate and no vigilance decrement). Furthermore, the new ANTI-Vea task assesses both components of vigilance together with others typical attentional functions.

Conclusions: The new attentional networks test developed here may be useful to provide a better understanding of the human attentional system. The role of sensitivity and response bias in the executive vigilance decrement are discussed.

Introduction

In the last 15 years, there has been considerable interest in developing behavioral tasks to assess several attentional functions simultaneously, such as the Attentional Network Test and its variations (J Fan et al., 2002; Ishigami et al., 2016; MacLeod et al., 2010). However, vigilance has been only lately included in these tasks as a direct and independent measure (i.e., the ANTI-V task, by Roca et al., 2011). Assessing vigilance can be quite complex when variables such as task demands, engagement, and time on task are took into account (Thomson, Besner, et al., 2015). Besides, vigilance might not be a unitary concept. Whilst this process is frequently described as the ability to detect critical events through long time periods (Warm et al., 2008), there are several studies that conceive vigilance as sustaining the tonic arousal level that is necessary to react quickly to stimuli from the environment (see, for example, Basner et al., 2013). Thus, in the present study, we have developed a new version of the attentional networks test (the ANTI-Vea), aiming at assessing independently these two components of vigilance, while measuring at the same time the classic attentional functions (i.e., phasic alertness, orienting, and executive control). We expect that the ANTI-Vea will contribute to the study of the attentional networks in different contexts and situations.

The Human Attentional System

Posner and collaborators proposed that the attentional system is organized by three independent neural networks, that may interact with each other (Jin Fan & Posner, 2004; S. E. Petersen & Posner, 2012; Posner & Dehaene, 1994; Posner & Petersen, 1990). First, the posterior orienting network involves the pulvinar nuclei of the thalamus and the superior colliculus, together with the temporo-parietal junction and the frontal eye fields. The orienting network directs attention towards potential spatial sources of relevant stimuli, and benefits from spatial cues that predict correctly these locations (Posner, 2014). Second, the alertness network is modulated by noradrenergic innervations of the locus coeruleus towards parietal and frontal regions in the right hemisphere. This network regulates two different functions: (a) phasic alertness, as a momentary increment of alertness produced by warning signals; and (b) vigilance, as the tonic alertness necessary to sustain performance over long time periods (Posner, 2008). Finally, the executive control network involves the anterior cingulate and the dorsolateral prefrontal cortices. In conflictive situations, this system regulates behavior to achieve our long-term goals (Funes et al., 2010; Shenhav et al., 2013).

In order to obtain an independent measure of each attentional network at the same time, Fan and collaborators developed the Attentional Network Test (ANT; Fan et al., 2002). This task consists in a flanker task, in which participants are to respond to the direction pointed by a central arrow (target) while ignoring the flanking arrows, which is useful to assess the executive control network (Botvinick et al., 2001; Eriksen & Eriksen, 1974). Additionally, for measuring phasic alertness, these stimuli can be preceded by a visual warning signal (i.e., double asterisk), or by no signal. Moreover, to assess the orienting network, stimuli can be anticipated by a spatial cue (i.e., an asterisk informing the correct location of the target) or a central cue (i.e., an asterisk without spatial information). Later on, aiming to analyze the interactions between the attentional networks, Callejas et al. (2004) dissociated the stimuli for measuring phasic alertness and orienting. In the ANT for Interactions (ANTI) task, an auditory tone is used as warning signal. In addition, the 100% predictive spatial cue is replaced by a visual non-predictive cue that indicates either the correct location of the target (valid cueing), or the opposite location (invalid cueing).

Interestingly, neither the ANT nor the ANTI included a direct measure of vigilance across time. Some studies proposed that overall performance, or the difference between the last and first block of trials, could be taken as indirect indexes of vigilance (Callejas et al., 2005; Ishigami & Klein, 2010). Thus, to provide a direct measure of this function, Roca and colleagues developed the ANTI-Vigilance task (ANTI-V; Roca et al., 2011). While solving the main flanker task, participants must remain vigilant to detect a low proportion of trials (25%) where the target appears largely displaced from its central position, either leftwards or rightwards. The ANTI-V proved to be useful to analyze the attentional functioning under total sleep deprivation (Roca et al., 2012) and to study drivers' attentional performance (Roca, Crundall, et al., 2013; Roca, Lupiáñez, et al., 2013).

The Multiple Concept of Vigilance

Vigilance is usually defined as the ability to sustain attention for detecting rare but critical events (see for example, See et al., 1997; Warm et al., 2008). To assess its functioning, psychologists have developed many behavioral tasks, like the Sustained Attention to Response Task (SART; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997), the Continuous Performance Test (Conners, 2000), or the Mackworth Clock Test (Lichstein, Riedel, & Richman, 2000). For example, in the SART, participants must watch and respond continuously to the presentation of any of the nine digits (0-9), while inhibiting the response to a pre-specified target digit (e.g., 3). Thus, participants have to decide constantly whether to execute a recurrent response, or to inhibit it and provide no response. Therefore, this set of tasks seems to analyze an 'executive' component of vigilance, focused on the accuracy in the detection of an infrequent target and the inhibition of a frequent response.

In the above-mentioned studies, the executive vigilance decrement is generally found as a tendency to detect less critical events across time (e.g., see Helton and Russell, 2015). There has been a long-standing discussion about whether this decrement is due to a loss in the sensitivity to discriminate unusual from usual events, or to a change in the response bias (Langner & Eickhoff, 2013; See et al., 1995). A recent review and an experimental demonstration conducted by Thomson et al. (2016) has shown that the decrement would be related to an increment in the response bias towards a more conservative criterion (i.e., participants attempt to commit fewer errors as time progresses).

On the other hand, vigilance also involves other aspects of behavior beyond the accuracy in detecting infrequent target. For example, in clinical neuropsychology, the term vigilance usually refers to the different levels of arousal during the sleep-wake cycle, without being associated with behavioral responsiveness (Oken et al., 2006). Accordingly, the Psychomotor Vigilance Test (PVT) is a behavioral task developed to analyze the maintenance of arousal through time (Lim & Dinges, 2008). The PVT requires the participants to stop, as fast as possible, a counter that appears on intervals from 2 to 10 seconds over a 10 minute period (Basner & Dinges, 2011). Using this paradigm, the vigilance decrement is observed as a progressive increment in both the mean and the variability of reaction time, usually analyzed under conditions of sleep deprivation (Basner et al., 2011; Loh et al., 2004). Therefore, this ‘arousal’ component of vigilance would be more involved in achieving and sustaining fast reactions to stimuli, without much control, i.e., without the consideration of alternative response options.

Objectives of the Current Study

In a recent review by Tkachenko and Dinges (2018), they state that “rigorous behavioral tasks capable of dissociating the different aspects of attention across varying levels of cognitive demand is imperative to understanding the relationship between the brain and behavior” (p. 44). This was the main goal of the current study. We have developed the Attentional Networks Test for Interactions and Vigilance – executive and arousal components (ANTI-Vea). With this new version of the attentional networks test, we aimed at solving previous issues in the assessment of executive vigilance (EV), and to incorporate a direct measure of arousal vigilance (AV), while measuring the classic attentional functions (i.e., phasic alertness, orienting, and executive control). Furthermore, with this novel task, we expected to observe the decrement across time in the two vigilance components in a single administration.

Note that in previous studies with the ANTI-V, despite the vigilance measure being sensitive to total sleep deprivation (Roca et al., 2012), the performance decrement could not be observed under regular sleep conditions. Furthermore, assessment of vigilance in the ANTI-V is only related to the executive component, as it requires detecting the appearance of an infrequent target (like in the SART). Besides, this measure has shown several issues in previous studies. To start with, the vigilance task was quite challenging, even for young, non-clinical participants. The average hit rate was between 45% and 60%, either using cars (Casagrande et al., 2017; Marotta et al., 2015; Roca et al., 2011, 2012; Roca, Crundall, et al., 2013; Roca, Lupiáñez, et al., 2013) or arrows as stimuli. In fact, participants tend to assume a very conservative response criterion (e.g., β between 7.5 and 10.3). Additionally, when the task was administered to older adults, about 44% of the sample had to be excluded due to an extremely poor performance (Moratal et al., 2015).

Thus, in a first experiment, we present a new version of the ANTI-V that we expected to be easier to perform than the previous version by Roca et al. (2011). This easier version will be more suitable to be used in populations for whom the previous version was not particularly fitted, such as older people (Moratal et al., 2015). In particular, we aimed to achieve a higher hit rate, and to observe the executive vigilance decrement within a single session. Next, in a second experiment, we present the ANTI-Vea, which incorporates an arousal vigilance measure, separated from the executive vigilance component. In both experiments, we decided to use arrows as stimuli (like in the ANT or ANTI tasks), as previous research has shown similar results in comparison to the original ANTI-V with cars (Bukowski et al., 2015; Morales et al., 2015).

Experiment #1: improving the executive vigilance measure

Our main goal in Experiment #1 was to overcome some limitations in previous studies with the ANTI-V, such as the low proportion of hits (Bukowski et al., 2015; Morales et al., 2015; Roca et al., 2011, 2012; Roca, Crundall, et al., 2013; Roca, Lupiáñez, et al., 2013). Thus, we compared vertically with horizontally displaced infrequent targets to assess vigilance. We expected the vertical displacement version to be easier to perform, as it will preclude the grouping of the target with the distracters, and thus infrequent targets would be more salient (see Fig. 1 in the next section). Finally, we expected this new version of the task to be suitable to observe the executive vigilance decrement across time. Following Thomson et al. (2016), the decrement was expected to be observed as a change in the response bias towards a more conservative criterion, rather than as a loss in sensitivity.

Materials and Methods

Participants

Participants (n = 51; 44 females) were students at the University of Granada, Spain (age: between 18 and 40 years, M = 19.72, SD = 2.11; education years: M = 13.88, SD = 0.98), who received course credits for their collaboration. They were randomly assigned to one of two groups, according to the task version administered (horizontal or vertical). Groups did not differ in age [t (48) = -0.09, p = .924] or education years [t (48) = 0.03, p = .972].

In this and the following experiment, participants were voluntarily recruited, and individually evaluated. All of them had normal or corrected to normal vision, and signed a written informed consent. The study was conducted according to the ethical standards of the 1964 Declaration of Helsinki (last update: Seoul, 2008), and was part of a larger research project approved by the University of Granada Ethical Committee (175/CEIH/2017).

Apparatus and Stimuli

Scripts were designed and run in E-Prime v2.0 Professional (Psychology Software Tools, Pittsburgh, PA). Responses were registered using a standard keyboard. The following stimuli were used: a black fixation cross (~7 pixels, px), a black asterisk (~13 px), a warning tone (2000 Hz), and five black arrows (50 px wide x 23 px high each arrow), pointing either leftwards or rightwards. Each arrow was horizontally separated by ~63 px from the adjacent arrows. In each trial, a random variability of ±2 px was applied on the horizontal and the vertical position of each arrow, to make more difficult the detection of the displaced infrequent targets. In executive vigilance trials, the central arrow displacement was larger and fixed to 8 px. The vertical and horizontal task versions were identical, except for the direction of the target displacement in the executive vigilance trials (see Fig. 1).

Procedure and Design

The ANTI-V includes two different type of trials: ANTI trials (i.e., the main flanker task for assessing phasic alertness, orienting, executive control, and their interactions) and executive vigilance (EV) trials, which require detecting infrequent stimuli. Stimuli sequence and timing for each type of trial is shown in Figure 1. In the ANTI trials (75%), participants had to respond according to the direction of the target (“C” for left, and “M” for right), while ignoring the flanking arrows. A warning signal and visual cue could anticipate the arrow appearance (see Fig. 1). The EV trials (25%) followed the same procedure, except that the target was horizontally or vertically displaced from the central position (see Fig. 1). In the EV trials, participants had to detect the large displacement by pressing the space bar, while ignoring the direction of the target.

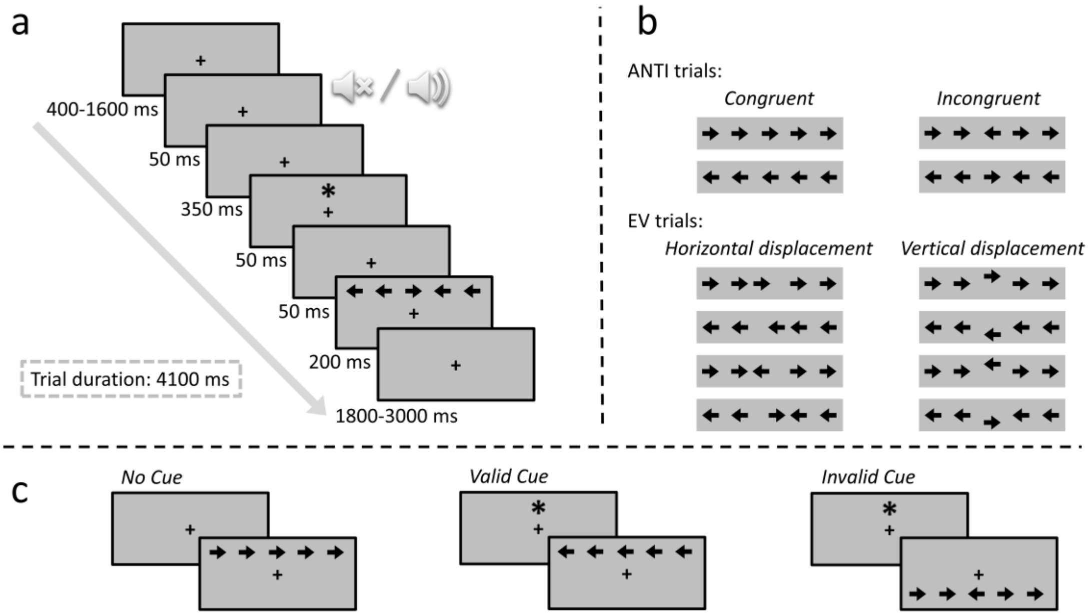

Figure 1. Experimental procedure and stimuli sequence. (a) Procedure of both ANTI and EV trials. The exact duration of the initial fixation point was randomly assigned. The final fixation point remained on screen until total trial time achieved 4100 ms. Responses were allowed until 2000 ms since the target presentation. (b) Target and flankers for ANTI and EV trials in the horizontal and the vertical task versions. (c) Examples of Visual cue conditions.

Instructions and practice blocks (with visual feedback) were given gradually, which is also an improvement from the original ANTI-V (Roca et al., 2011). Participants were encouraged to keep their eyes on the fixation point all the time. First, standard instructions for the ANTI trials were given, followed by 16 practice ANTI trials. Next, instructions for the EV trials were presented, followed by 32 practice trials (including 16 ANTI and 16 EV in randomized order). Finally, participants performed an additional practice block of 32 randomized trials without feedback (24 ANTI and 8 EV; which is half of one experimental block). Then, before starting the experimental trials, participants could consult the researcher in charge any doubt about instructions, or repeat the last practice block.

The session included six experimental blocks of 64 randomized trials (48 ANTI and 16 EV per block), with no break and no feedback. The 48 ANTI trials had the following factorial design: Warning signal (No tone/Tone) × Visual Cue (Invalid/No Cue/Valid) × Congruency (Congruent/Incongruent). In the EV trials, one more factor was added to the previous design: Displacement direction (Left/Right or Up/Down, respectively for the horizontal or the vertical task version). The 16 EV trials per block were randomly selected from all the possible trial combinations.

Data Analysis

Analyses were conducted in Statistica 8.0 (StatSoft Inc.), and data figures were made with Matplotlib 1.5.3 (Hunter, 2007) software. In all the analyses, the significance level was established at .05, and confidence intervals at 95%. A participant with more than 25% of errors (i.e., a performance unusually low for the typical ANTI task), and another participant with an extreme average reaction time (which was above 2.5 standard deviations from the group mean), were excluded from further analysis. In addition, one more participant was excluded due to technical issues. Thus, the final sample included 24 participants per group.

For the analysis of RT, trials with incorrect responses (7.08%) or with a RT smaller than 200 ms or higher than 1500 ms (2.16%) were excluded. Then, for the ANTI trials, repeated measures ANOVAs were conducted on both RT and percentage of errors, including Warning signal (No tone/Tone), Visual cue (Invalid/No cue/Valid), and Congruency (Congruent/Incongruent) as within-participants factors, and Task version (Horizontal/Vertical) as a between-participants factor.

For the EV trials, data from the different conditions of the warning signal, visual cue, and congruency variables were collapsed. Then, Signal Detection Theory metrics (SDT; Stanislaw and Todorov, 1999) were computed per block of trials, in order to analyze vigilance changes across time. Hits were calculated as the proportion of displaced targets detected correctly, and False Alarms (FAs) as the proportion of space bar responses (i.e., the response for infrequent stimuli) given to non-displaced targets. Next, non-parametric indexes of sensitivity (A') and response bias (B'') were obtained (J. B. Grier, 1971). The non-parametric indexes are distribution-free, and can be fitted to the data without assuming a normal distribution (as with *d'* and β). Therefore, A' and B" can be perfectly computed when hits have a ceiling (i.e., 100%) and FAs a floor effect (i.e., 0%), without needing to replace those scores (Stanislaw & Todorov, 1999; Thomson et al., 2016). Last, mean and standard deviation (SD) of RT was obtained only for hits. Then, six repeated measures ANOVAs were separately conducted including Block (6 levels) as within-participants factors, and Task Version (Horizontal/Vertical) as a between-participants factor, one for each dependent variable: Hits, FAs, A' (sensitivity), B" (response bias), mean RT, and the SD of RT.

Results

Phasic Alertness, Orienting and Executive Control

Mean RT and accuracy for each ANTI condition are shown in Table 1.

Table 1. Mean and standard deviation (in parentheses) for correct RT and accuracy (percentage of errors) of Experiment 1 for each condition of the ANTI factorial design in the horizontal and vertical ANTI-V versions: Warning signal (No tone/Tone) x Visual cue (Invalid/No cue/Valid) x Congruency (Congruent/Incongruent).

		No tone			Tone		
		Invalid	No cue	Valid	Invalid	No cue	Valid
Reaction Time							
Horizontal	Congruent	645 (74)	666 (92)	634 (94)	630 (85)	609 (91)	596 (79)
	Incongruent	739 (103)	722 (94)	709 (107)	737 (97)	691 (101)	683 (101)
Vertical	Congruent	617 (106)	625 (90)	589 (97)	587 (108)	549 (85)	543 (79)
	Incongruent	655 (90)	644 (91)	612 (89)	634 (102)	608 (88)	577 (85)
Accuracy							
Horizontal	Congruent	3.8 (6.0)	5.4 (5.6)	6.4 (7.4)	3.5 (4.2)	2.8 (4.9)	4.3 (5.7)
	Incongruent	13.0 (9.1)	14.6 (10.3)	15.5 (11.8)	10.6 (8.7)	13.5 (9.5)	14.6 (10.8)
Vertical	Congruent	4.0 (4.0)	4.0 (4.8)	3.8 (5.2)	2.8 (4.5)	3.1 (4.8)	2.6 (4.4)
	Incongruent	5.0 (5.2)	6.6 (5.5)	4.0 (6.1)	5.0 (8.1)	2.6 (3.4)	3.1 (3.9)

Reaction Time

Significant main effects were found for the three within-participants factors: Warning signal [*F* (1, 46) = 109.40, $p < .001$, $\eta_p^2 = .70$], Visual cue [*F* (2, 92) = 42.36, $p < .001$, $\eta_p^2 = .48$], and Congruency [*F* (1, 46) = 159.75, $p < .001$, $\eta_p^2 = .77$]. A main effect of Task Version was also observed [*F* (1, 46) = 7.51, $p = .008$, $\eta_p^2 = .14$], with lower RT for the Vertical (M = 603 ms; SD = 88) than for the Horizontal version (M = 669 ms; SD = 84).

The following interactions were also significant: Warning signal × Visual cue [*F* (2, 92) = 12.03, $p < .001$, $\eta_p^2 = .21$], Warning signal × Congruency [*F* (1, 46) = 19.54, $p < .001$, $\eta_p^2 = .30$], and Visual cue × Congruency [*F* (2, 92) = 5.53, $p = .005$, $\eta_p^2 = .11$]. The three within-participants factors did not interacted significantly [F (2, 92) = 1.99, p = .141, η_p^2 = .04]. Finally, Task Version only interacted with Congruency [F (1, 46) = 24.34, p < .001, η_p^2 = .35]. The interference effect (i.e., incongruent minus congruent conditions) was smaller for the Vertical (37 ms) than for the Horizontal version (83 ms).

Accuracy (% of errors)

Significant main effects were found for Warning signal [F (1, 46) = 7.80, p = .007, η_p^2 = .14] and Congruency [F (1, 46) = 51.23, p < .001, η_p^2 = .53], but not for Visual cue [F (2, 92) 1.56, p = .215, η_p^2 = .03]. The main effect of Task Version was also observed [F (1, 46) = 15.03, p < .001, η_p^2 = .24], with fewer errors for the Vertical (M = 3.89%; SD = 3.10) than for the Horizontal version (M = 8.99%; SD = 5.65).

Congruency interacted with Task Version [F (1, 46) = 33.02, p < .001, η_p^2 = .41], like in the RT results. Again, the interference effect was smaller for the Vertical (1.01%) than for the Horizontal version (9.26%). The remaining interactions did not reach the significance level, except for Visual cue × Task Version [F (2, 92) = 5.83, p = .004, η_p^2 = .41]. In the Vertical version, the facilitation effect of cueing was found as usual (valid = 3.38%; no cue = 4.07%; invalid = 4.21%), whereas in the Horizontal version responses were less accurate for valid cue trials than for the remaining ones (valid = 10.19%; no cue = 9.07%; invalid = 7.72%).

Executive Vigilance Decrement

Reaction Time

The main effect of Block were not significant neither for mean RT [F (5, 215) = 1.84, p = .106, η_p^2 = .04] nor for the SD of RT [F (5, 210) = 1.23, p = .294, η_p^2 = .03]. The main effect of Task version was only found for mean RT [F (1, 43) = 13.85, p < .001, η_p^2 = .24], with faster

RT for the Vertical (M = 738 ms; SD = 95) than for the Horizontal version (M = 845 ms; SD = 95). No significant interactions were observed.

Hits and False Alarms

Both Hits [*F* (5, 230) = 5.81, $p < .001$, $\eta_p^2 = .11$] and FAs [*F* (5, 230) = 3.72, $p = .002$, $\eta_p^2 = .07$] showed a significant decrement across Blocks, as observed in Figure 2. Additionally, main effects of Task Version were observed for both Hits [*F* (1, 46) = 4.10, $p = .048$, $\eta_p^2 = .08$] and FAs [*F* (1, 46) = 14.55, $p < .001$, $\eta_p^2 = .24$]. Hits rate was higher in the Vertical (M = 61.84%; SD = 19.24) than in the Horizontal version (M = 51.04%; SD = 17.71), whereas FAs rate was lower in the Vertical (M = 2.31%; SD = 2.92) than in the Horizontal version (M = 6.85%; SD = 5.04). No significant interactions were found.

Sensitivity and Response bias

As observed in Figure 2, a significant increment across Blocks was found for Response Bias (B”) [*F* (5, 230) = 4.59, $p < .001$, $\eta_p^2 = .09$], while Sensitivity (A’) did not change significantly [*F* (5, 230) = 0.84, $p = .522$, $\eta_p^2 = .02$]. The analysis of Sensitivity showed a main effect of Task Version [*F* (1, 46) = 14.93, $p < .001$, $\eta_p^2 = .24$], with higher sensitivity in the Vertical (A’ = .89) than in the Horizontal version (A’ = .84). Response Bias did not differ significantly between Task Versions [*F* (1, 46) = 2.38, $p = .129$, $\eta_p^2 = .05$] (Vertical B” = .77; Horizontal B” = .59). No significant interactions were found.

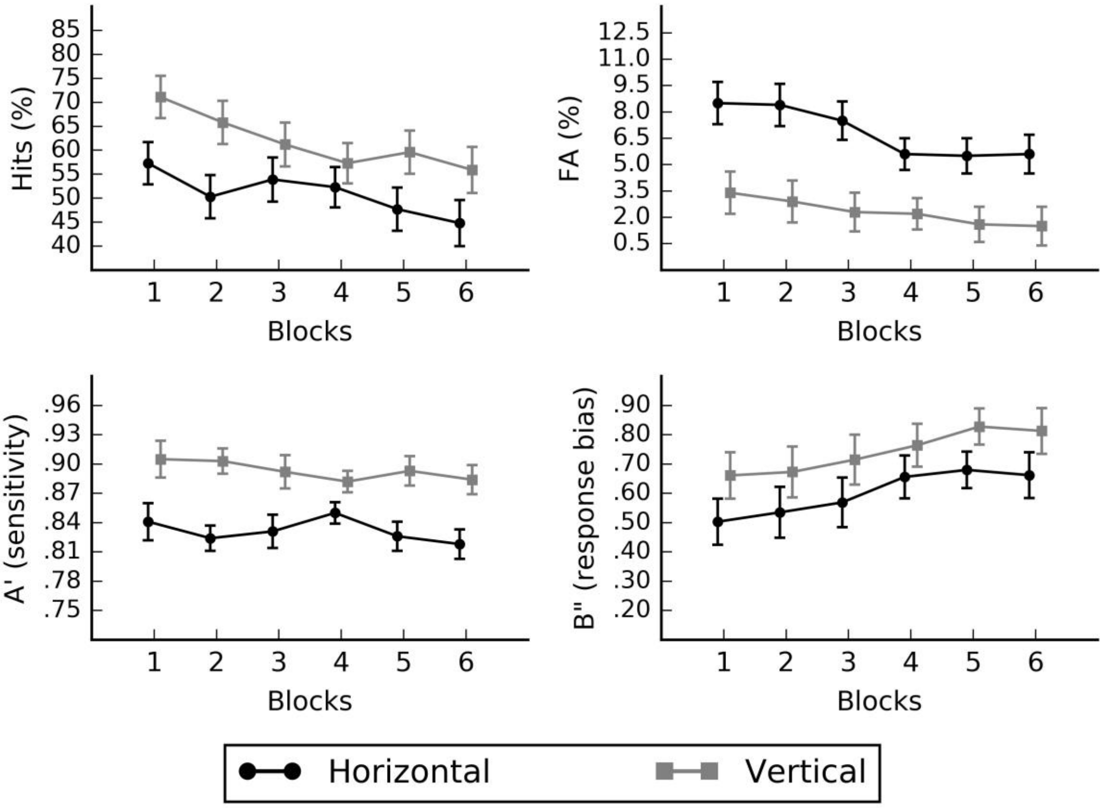

Fig 2. Executive Vigilance decrement in ANTI-V task versions. Performance across time on task in Hits (top left graph), FA (top right graph), A’ sensitivity (bottom left graph), and B” response bias (bottom right graph). Bars represents SE.

Discussion

The first experiment aimed at improving the measurement of the executive component of vigilance in the ANTI-V. We expected the vertical displacement of the target to be more easily detected than the horizontal displacement of the original ANTI-V by Roca et al. (2011). In addition, with this manipulation, we expected to succeed in observing the vigilance decrement across time, which was not found previously with this task (Roca et al., 2012). Finally, we predicted no differences in the classic attentional measures between the two task versions.

The obtained results demonstrate that the vertical version of the task is more suitable to assess executive vigilance. Specifically, we found a higher percentage of hits and fewer FAs, and thus higher sensitivity than with the horizontal version. In previous studies with the ANTI-V, the horizontal displacement resulted quite difficult to be detected, either with cars (Marotta et al., 2015; Roca et al., 2011) or arrows (Bukowski et al., 2015; Morales et al., 2015) as stimuli.

More importantly, an executive vigilance decrement was found, which interestingly was observed as an increment in response bias, rather than as a loss in sensitivity. Recently, Thomson et al. (2016) reviewed several studies in which a floor effect in the FAs might be leading to an incorrect analysis of the vigilance decrement. While the decrement is usually interpreted as a loss in sensitivity, the FAs floor effect could be masking an increment in the response bias across time. Thus, Thomson et al. (2016) developed a novel vigilance paradigm and conducted an experiment aiming to increase the FAs. Although observing a FAs rate of ~30% in the first task period, no increment of FAs across time was found, necessary to reveal some loss in sensitivity (Thomson et al., 2016). Instead, and in line with our findings in the first experiment of this paper, both hits and FAs decreased over time, therefore demonstrating an increment in response bias.

Finally, regarding the analysis of the ANTI trials, we did not anticipate several differences found between the two task versions. In general, participants had faster and more accurate responses in the vertical than in the horizontal version. In addition, the usual cueing effect (valid < no cue < invalid; see, for example, Merritt et al., 2007; Posner, 2014) was found in both tasks with RT data, but only in the vertical version of the task with accuracy data. Moreover, regarding the executive control, the interference effect seems to be reduced to the half or less in the vertical version, as compared to previous versions of the task, like the ANT (J Fan et al., 2002), the ANTI (Callejas et al., 2004), and the ANTI-V (Morales et al., 2015; Roca et al., 2011).

In summary, the results obtained seem to support that the vertical version of the task is easier to perform than the horizontal one, and that it is a valid task to observe the vigilance decrement. In the following experiment, we aim at replicating these findings and, additionally, we will include an arousal vigilance measure. The proposed new task may result suitable to analyze separately the two vigilance components, executive and arousal, and their decrement over time.

Experiment #2: adding an arousal vigilance measure

The main goal of this experiment was to design a task (ANTI-Vea) that could measure simultaneously the typical attentional functions, together with the two components of vigilance: executive vigilance (i.e., response control to discriminate infrequent from frequent events), and arousal vigilance (i.e., sustaining a tonic arousal level to achieve a fast reaction). Regarding the executive vigilance, we expected to replicate the decrement as an increment in the response bias, and not as a sensitivity loss (Thomson et al., 2016). In addition, we also designed our new task to be suitable for observing the decrement in arousal vigilance, probably as a progressive increment in both the mean and the variability of the reaction time.

Additionally, we expected to replicate the findings observed in Experiment #1 between the horizontal and vertical task versions on executive vigilance and on the interference effect. Therefore, two different versions of the new ANTI-Vea task were compared, like in Experiment #1 (horizontal and vertical). We expected executive vigilance trials to be again easier to complete for the vertical than the horizontal version of the task. However, probably the inclusion of the arousal vigilance measure could make the whole task more difficult, because the attentional set needed to resolve three tasks simultaneously should be larger (i.e., three different instructions to comply with, instead of two). As a result, some differences between the two task versions of the ANTI-Vea could be even larger (e.g., overall RT and the percentage of errors in the ANTI trials, and the interference effects) than in Experiment #1.

Materials and Methods

Participants

Participants (n = 80; 40 females) were students or recently graduated at the National University of Córdoba, Argentina (age: between 18 and 40, M = 25.17, SD = 6.05; education years: M = 14.53; SD = 1.98). They were randomly assigned to one of two groups, according to the task version administered (horizontal or vertical). The groups did not differ in age [*t* (78) = -0.44, *p* = .660], or education years [*t* (78) = 0.73, *p* = .466].

Apparatus and Stimuli

Stimuli were the same as in Experiment #1. In addition, a red millisecond down counter (~110 px height each number) was intermittently presented at fixation, to obtain an arousal vigilance measure.

Procedure and Design

In the ANTI-Vea task, there are three different types of trials: ANTI, EV, and arousal vigilance (AV). For the ANTI and the EV trials (respectively, 60% and 20% of the trials), the stimuli sequence and timing, response keys, and design, were the same as in Experiment #1 (see Fig. 1). In the AV trials (20%, see Fig. 3), no tone, visual cue, or arrows were presented. These trials started as the ANTI and EV trials, and then the fixation point remained fixed in the screen for 500 ms (i.e., the same duration as for the tone plus the visual cue signals in the ANTI and EV trials). Next, a red millisecond counter appeared in the center of the screen, starting at 1000 and going down to zero. Participants were asked to stop the counter as fast as they could, by pressing any key of the keyboard.

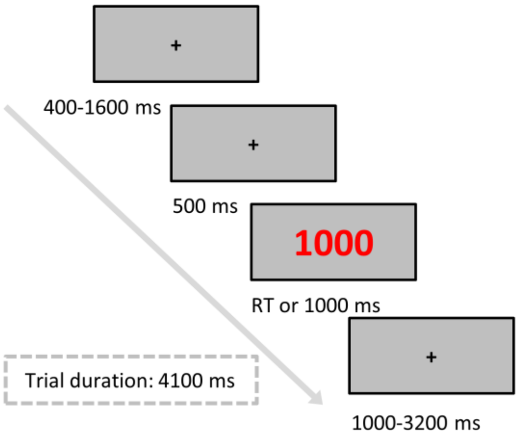

Figure 3. Stimuli sequence of the AV trials in the ANTI-Vea. Responses were allowed until 2000 ms since the down counter presentation.

Before starting the experimental task, participants performed several practice blocks with visual feedback. First, instructions to resolve the ANTI trials were given, with a practice block of 16 ANTI trials. Next, instructions about the EV trials were presented, with a practice block of 32 randomized trials (16 ANTI and 16 EV). Then, instructions for the AV trials were given, followed with a practice block of 48 randomized trials (16 ANTI, 16 EV, 16 AV). Finally, participants performed a last practice block of 40 randomized trials (24 ANTI, 8 EV and 8 AV; half of one experimental block), without visual feedback. At this point, if participants still had any doubt, they could ask questions or perform again the last practice block. Otherwise, they continued with the experimental section of the task, that included six blocks of 80 randomized trials (48 ANTI, 16 EV and 16 AV per block), with no pause and no visual feedback. The factorial design of the ANTI trials and the selection procedure for EV trials was the same as in Experiment #1.

Data Analysis

The data from six participants with more than 25% of errors in the ANTI trials were excluded. Then, for the ANTI and the EV trials, the analyses conducted were the same as in Experiment #1. For RT analyses, incorrect responses (9.79%) and with RT smaller than 200 ms and higher than 1500 ms (2.40%) were excluded.

For the AV trials, the mean and SD of RT were obtained per block. Note that in the PVT (Lim & Dinges, 2008), one typical measure is the analysis of lapses (i.e., late responses to the millisecond down counter), generally considered as a response time equal to or larger than 500 ms (Basner & Dinges, 2011). The mean (and median) RT in the PVT is usually around 250 ms when the lapses threshold is stablished at 500 ms (Basner et al., 2011; Blatter et al., 2006; Drummond et al., 2005; Lee et al., 2010; Lim & Dinges, 2008; Loh et al., 2004). However, in the ANTI-Vea task, it was observed a higher mean and median RT (close to 480 ms), probably due to the inclusion of the ANTI and the EV trials together with the millisecond down counter. Therefore, the lapses in the ANTI-Vea task were defined as responses larger than 600 ms. This criterion was selected after comparing the percentage of lapses across blocks with four different thresholds: > 500 ms, > 600 ms, > mean + 1 SD of RT by participant, > mean + 1 SD of RT by group. Finally, three repeated measures ANOVAs were separately conducted including task Block (6 levels) as a within-participants factor, and Task Version (Horizontal/Vertical) as a between-participants factor, one for each dependent variable: mean RT, SD of RT, and lapses percentage.

Results

Phasic Alertness, Orienting and Executive Control

Mean RT and accuracy for the ANTI trials are shown in Table 2.

Table 2. Mean and standard deviation (in parentheses) for correct RT and accuracy (percentage of errors) of Experiment 2 for each condition of the ANTI factorial design in the horizontal and

vertical ANTI-Vea versions: Warning signal (No tone/Tone) x Visual cue (Invalid/No cue/Valid) x Congruency (Congruent/Incongruent).

		No tone			Tone		
		Invalid	No cue	Valid	Invalid	No cue	Valid
Reaction Time							
Horizontal	Congruent	702 (132)	718 (122)	677 (122)	678 (119)	663 (127)	656 (131)
	Incongruent	805 (119)	791 (147)	766 (127)	807 (142)	759 (141)	763 (137)
Vertical	Congruent	648 (88)	650 (93)	628 (94)	641 (87)	618 (94)	597 (86)
	Incongruent	685 (81)	686 (90)	661 (93)	695 (90)	645 (87)	626 (77)
Accuracy							
Horizontal	Congruent	6.6 (6.5)	6.3 (5.3)	6.9 (7.4)	3.2 (4.2)	4.4 (5.2)	5.7 (7.3)
	Incongruent	16.2 (11.5)	15.4 (8.3)	15.4 (9.7)	13.3 (9.7)	13.7 (10.8)	15.7 (10.6)
Vertical	Congruent	7.3 (7.6)	6.3 (6.6)	9.1 (6.8)	5.9 (7.0)	4.2 (5.2)	6.8 (6.7)
	Incongruent	6.1 (8.5)	7.1 (6.6)	7.1 (7.0)	4.3 (4.4)	3.5 (4.4)	7.1 (6.8)

Reaction Time

Significant main effects were found again for the three within-participants factors: Warning signal [F (1, 72) = 55.49, p < .001, η_p^2 = .44], Visual cue [F (2, 144) = 64.49, p < .001, η_p^2 = .47], and Congruency [F (1, 72) = 231.20, p < .001, η_p^2 = .76]. The main effect Task Version was also significant [F (1, 72) = 11.85, p < .001, η_p^2 = .14], with lower RT for the Vertical (M = 648 ms; SD = 82) than for the Horizontal version (M = 729 ms; SD = 123).

As in the previous experiment, and it is usually found with the ANTI and ANTI-V tasks, the Warning signal × Visual cue [F (2, 144) = 20.09, p < .001, η_p^2 = .22], Warning signal × Congruency [F (1, 72) = 6.42, p = .013, η_p^2 = .08], and Visual cue × Congruency [F (2, 144) = 10.94, p < .001, η_p^2 = .13] interactions were significant. The three-way within-participants factors interaction did not reach significance [F (2, 144) = 0.97, p = .381, η_p^2 = .01].

Task Version modulated Congruency [F (1, 72) = 50.51, $p < .001$, $\eta_p^2 = .41$]: a much reduced interference effect was again observed in the Vertical (36 ms), as compared to the Horizontal version (100 ms). Finally, an interaction was found between Warning signal, Visual cue, and Task Version [F (2, 144) = 5.36, $p = .005$, $\eta_p^2 = .07$]. In the Vertical version, the warning tone increased the facilitation effect of cueing (valid = 612 ms; no cue = 631 ms; invalid = 668 ms) with respect to the absent tone condition (valid = 645 ms; no cue = 668 ms; invalid = 667 ms). Instead, in the Horizontal version, the cueing effect was similar for the tone (valid = 709 ms; no cue = 711 ms; invalid = 742 ms) and no tone trials (valid = 721 ms; no cue = 754 ms; invalid = 754 ms).

Accuracy (% of errors)

Significant main effects were observed for all the within-participants factors: Warning signal [F (1, 72) = 16.43, $p < .001$, $\eta_p^2 = .19$], Visual cue [F (2, 144) = 8.27, $p < .001$, $\eta_p^2 = .10$], and Congruency [F (1, 72) = 46.60, $p < .001$, $\eta_p^2 = .39$]. The Task Version effect was also significant [F (1, 72) = 12.71, $p < .001$, $\eta_p^2 = .15$]. As in Experiment#1, responses were more accurate in the Vertical (M = 6.24%; SD = 4.15) than in the Horizontal version (M = 10.23%; SD = 5.42).

Only the Congruency × Task Version interaction reached significance [F (1, 72) = 63.08, $p < .001$, $\eta_p^2 = .47$]. As with RT, a reduction in the interference effect was observed in the Vertical (- 0.71%) as compared to the Horizontal version (9.44%).

Executive Vigilance Decrement

Reaction Time

As in Experiment #1, mean RT [*F* (5, 350) = 0.75, *p* = .583, η_p^2 = .01] and the SD of RT [*F* (5, 345) = 0.62, *p* = .683, η_p^2 = .01] did not change significantly across Blocks. The main effect of Task Version was only found for mean RT [*F* (1, 70) = 10.55, *p* = .002, η_p^2 = .13], with smaller RT for the Vertical (M = 776 ms; SD = 80) than for the Horizontal version (M = 863 ms; SD = 128). No significant interactions were found.

Hits and False Alarms

A significant main effect of Block was observed for both Hits [*F* (5, 360) = 3.94, *p* = .001, η_p^2 = .05] and FAs [*F* (5, 360) = 2.46, *p* = .033, η_p^2 = .03]. Planned comparisons confirmed a linear decrement for both Hits [*F* (1, 72) = 10.87, *p* = .001] and FAs [*F* (1, 72) = 4.42, *p* = .039], as observed in Figure 4.

Additionally, the main effect of Task Version was also significant for both Hits [*F* (1, 72) = 12.64, *p* < .001, η_p^2 = .15] and FAs [*F* (1, 72) = 14.43, *p* < .001, η_p^2 = .17]. Hit rate was higher in the Vertical (M = 74.89%; SD = 17.85) than in the Horizontal version (M = 58.62%; SD = 21.43), and FAs rate was smaller in the Vertical (M = 4.24%; SD = 3.03) than in the Horizontal version (M = 7.97%; SD = 5.18). No significant interactions were found.

Sensitivity and Response bias

The main effect of Block was only found for Response Bias (B”) [*F* (5, 360) = 3.17, *p* = .008, η_p^2 = .04], but not for Sensitivity (A’) [*F* (5, 360) = 1.66, *p* = .143, η_p^2 = .02]. As can be observed in Figure 4, Response Bias increased linearly with time on task [*F* (1, 72) = 1.72, *p* = .006]. In addition, planned comparisons revealed that the linear component of Sensitivity for each task version did not reach significance: Vertical [*F* (1, 72) = 3.08, *p* = .083] and Horizontal version [*F* (1, 72) = 0.73, *p* = .395].

In contrast, the main effect of the Task Version was only found for Sensitivity [*F* (1, 72) = 26.33, *p* < .001, η_p^2 = .27], with a higher discrimination in the Vertical (A' = .92) than in the Horizontal version (A' = .85). The Task version effect was not observed for Response Bias [*F* (1, 72) = 0.06, *p* = .800, η_p^2 = .01] (Horizontal B" = .48; Vertical B" = .55). No significant interactions were found.

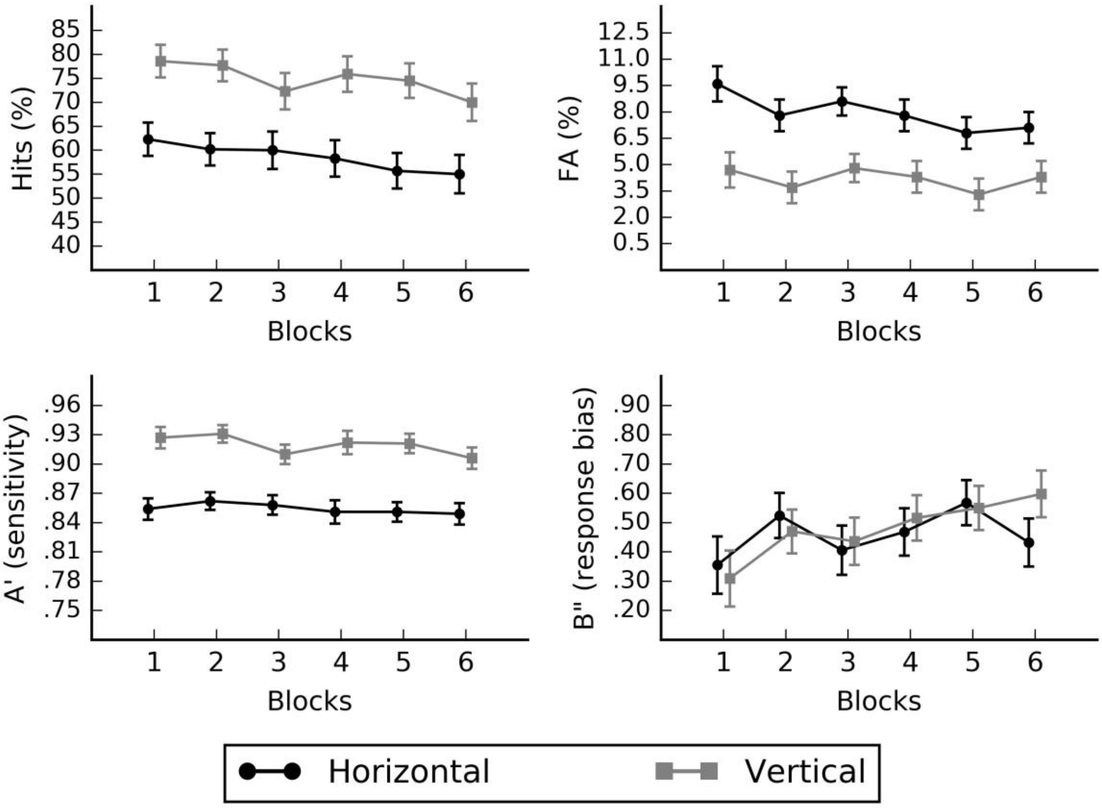

Figure 4. Executive Vigilance decrement in ANTI-Vea task versions. Performance across time on task in Hits (top left graph), FA (top right graph), A' sensitivity (bottom left graph), and B" response bias (bottom right graph). Bars represents SE.

Because the increment in Response Bias seems to be linearly different in each task version (see Fig. 4), planned comparisons were performed to test the polynomial linear component. The contrast between both task versions was not significant [*F* (1, 72) = 1.99, *p* = .162]. However, when the linear component of Blocks was analyzed considering one single task version, the B” linear increment was significant for the Vertical [*F* (1, 72) = 9.08, *p* = .003], but not for the Horizontal [*F* (1, 72) = 0.92, *p* = .339] version.

Arousal Vigilance Decrement

Mean and SD of Reaction Time, and Lapses percentage

Significant main effects of Block were found for mean RT [*F* (5, 360) = 3.61, *p* = .003, η_p^2 = .05], the SD of RT [*F* (5, 360) = 6.79, *p* < .001, η_p^2 = .09], and Lapses percentage [*F* (5, 360) = 5.11, *p* < .001, η_p^2 = .07]. All these variables increased linearly with time on task, as it is shown in Figure 5: mean RT [*F* (1, 72) = 8.50, *p* = .004], the SD of RT [*F* (1, 72) = 16.79, *p* < .001], and Lapses percentage [*F* (1, 72) = 13.03, *p* < .001]. Task version main effect was not observed either for mean RT (Horizontal overall = 484 ms; Vertical overall = 479 ms), the SD of RT (Horizontal overall = 83; Vertical overall = 81) or Lapses percentage (Horizontal overall = 9.83%; Vertical overall = 7.70%). No significant interactions were found.

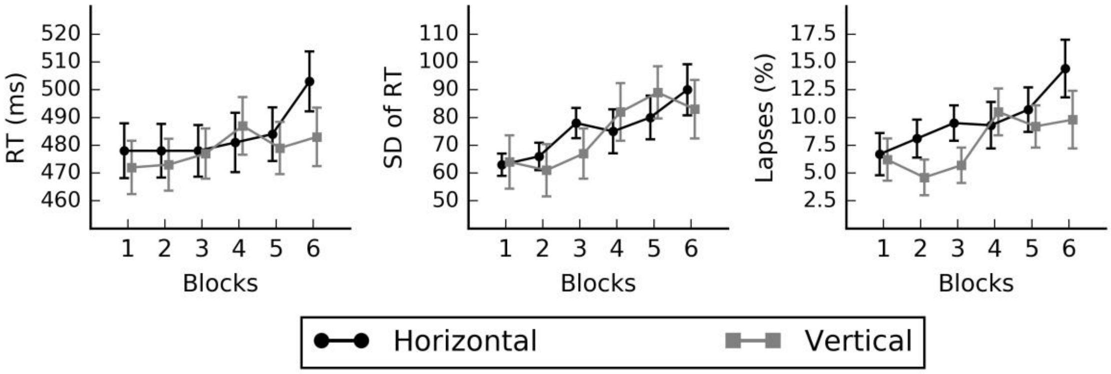

Figure 5. Arousal Vigilance decrement in ANTI-Vea task versions. Performance across time on task in mean RT (left graph), SD of RT (center graph) and Lapses percentage (right graph) for each ANTI-Vea task version. Bars errors represents SE.

Discussion

The ANTI-Vea task developed in Experiment #2 aimed to assess the executive and arousal components of vigilance separately, while also measuring the classic attentional functions. With this novel task, we expected to observe the decrement in the two components of vigilance in a single session. Additionally, we looked to replicate the findings of Experiment #1, and thus observe that the vertical version was easier to complete than the horizontal one. Last but not least, we expected that the inclusion of the arousal vigilance measure would not alter the assessment of the classic attentional functions (Callejas et al., 2004).

Regarding the arousal vigilance measure, no differences were observed between the vertical and horizontal task versions in the mean, the SD of RT, or the percentage of lapses. It should be noted that the overall RT found with the ANTI-Vea was ~200 ms slower than in several studies with the PVT task (Basner et al., 2011; Blatter et al., 2006; Drummond et al., 2005; Lee et al., 2010; Lim & Dinges, 2008; Loh et al., 2004). In the PVT, the inter-stimuli-interval (ISI) is set between 2 to 10 seconds (Basner & Dinges, 2011), while in the ANTI-Vea the ISI is ~16 seconds on average (i.e., every 4 trials). Moreover, and perhaps more importantly, during the ISI in the ANTI-Vea, participants may receive several visual and auditory signals, whiles performing the flanker and executive vigilance tasks. Therefore, it could be possible that increasing the task demands and the number of stimuli between two down counter may explain the larger overall RT observed in the arousal vigilance component. Maybe the ANTI-Vea would be useful to study, from a new perspective, the decrement of arousal vigilance under conditions of sleep loss (Basner et al., 2013; Krause et al., 2017), together with executive vigilance and executive control (Perrier, Chavoix, & Bocca, 2015; Roca et al., 2012).

For the executive vigilance, the vertical version of the ANTI-Vea task did not produce a ceiling effect in hits (overall ~75%) neither a floor effect in FAs (overall ~4%), as other simple and monotone vigilance tasks usually do (for a review, see Thomson et al., 2016, 2015). Indeed, the hit rate reported in the current study is higher than the usual results in previous ANTI-V studies (45% to 60%). Most important, as both hits and FAs showed a decrement across time, the progressive increment in response bias was replicated (being more pronounced in the vertical than in the horizontal version), like in Experiment #1.

Finally, the results obtained in the second experiment seem to confirm that the displacement of the infrequent target in one dimension or the other impacts also the resolution of the embedded flanker task. In the vertical version, responses were faster and more accurate in general, and a reduced interference effect was found, as in Experiment #1. In addition, the warning signal increased the cueing facilitation effect only in the vertical version, an interaction that has been observed previously with other attentional networks tasks (Callejas et al., 2005; Roca et al., 2011; Roca, Crundall, et al., 2013).

General Discussion

The current study aimed to develop a new version of the attentional network test, the ANTI-Vea, to assess in a single session the classic attentional functions, together with the executive and arousal vigilance components. The observed pattern of results seems to show that the task provided the expected measures. We tested the new attentional task on young adults between 18 and 40 years, and replicated the main findings across different countries. The new task provides the usual measures of phasic alertness, orienting and executive control, and new measures (i.e., vigilance decrements) of both arousal and executive vigilance. Furthermore, the new task seems to be easier to perform, which makes it more suitable to test attentional performance in different populations as, for example, in the elderly, where the functioning of the executive control and alertness networks might be compromised (Williams et al., 2016; Zhou, Fan, Lee, Wang, & Wang, 2011). Thus, we expect the task developed here to be useful for future studies aiming to understand the development of the attentional networks across adulthood, something that could not be achieved with the previous version of the ANTI-V (Moratal et al., 2015).

Importantly, the vertical version of the task proposed here resulted suitable to observe the executive vigilance decrement, as an increment in response bias. Several vigilance studies have observed this decrement as a loss in sensitivity, explaining such phenomenon as a depletion of attentional resources (for a review, see Warm et al., 2008). Moreover, it has been proposed that requiring a higher cognitive effort, or increasing the working memory load during the vigilance activity, might produce a larger decrement (Head & Helton, 2014; Helton & Russell, 2011). However, with the ANTI-Vea task, participants resolved three tasks simultaneously with a high cognitive load, and sensitivity did not change across time. In contrast, the executive vigilance decrement was observed as an increment in the response bias, consistently with Thomson et al. (2016).

It should be noted that recently, the findings by Thomson et al. (2016) received several comments by Fraulini et al. (2017). These authors objected the way Thomson et al. (2016) analyzed SDT metrics, as they dissociated three stimuli distributions (signal, noise, and 'lures') in a novel vigilance paradigm. Moreover, Fraulini et al. (2017) pointed out that data was collected online, without controlling the experimental context. Nevertheless, the experiments conducted in the present study do not share these potential flaws identified by Fraulini et al. (2017), still supporting the idea that executive vigilance decrement is best interpreted as an increment in response bias rather than a loss in sensitivity.

On the other hand, with the ANTI-Vea we could also analyze the arousal vigilance decrement. The duration of the ANTI-Vea (33 minutes approximately) is larger than the PVT, generally about 10 minutes (Basner & Dinges, 2011). The PVT has been widely used to analyze the arousal vigilance decrement under conditions of total (Lamond et al., 2008) or partial (Basner et al., 2011) sleep deprivation. In these sleep loss studies, the PVT is usually administered every one or two hours, and the decrement is analyzed across the total time of evaluation. For example, using the PVT, Loh et al. (2004) observed a linear decrement higher than 50 ms just in one night of sustained wakefulness (from 11 p.m. to 6 a.m.). Within the first two hours of evaluation, participants in the latter study showed a decrement close to 20 ms, similar to the results obtained here with the ANTI-Vea task.

With the vertical version of the ANTI-Vea task, we observed a reduced hit rate (~75%) for EV, and a larger overall RT (479 ms) for AV, in comparison to the performance usually observed with the SART and PVT tasks respectively. It could be possible that the increment on task demands (i.e., to solve three tasks simultaneously, instead of only one) might modulate performance on the vigilance components. To address this issue, we conducted another study in our laboratory (Luna et al., Unpublished results), in which participants responded to either the executive vigilance task alone (i.e., as in the SART) or the arousal vigilance alone (i.e., as in the PVT), ignoring any other stimuli of the ANTI-Vea, which were nevertheless presented. When participants only responded to the executive vigilance task, we found the classic ceiling effect on hits (~90%), with a more pronounced decrement (2.33% per block) than with the vertical version of the ANTI-Vea (1.40% per block). When participants only responded to the arousal vigilance task, we found a faster overall RT (391 ms), together with a three times larger decrement (7.65 ms increment per block), than in the current research (2.50 ms per block).

Whilst in the present study our main goal was to measure separately the executive and arousal vigilance components using a single task, further studies will be necessary to analyze if these components can be dissociated from one another. Previously, Sarter et al. (2001) have proposed that vigilance may be conceived as separated from the arousal components of attention. They described vigilance as a behavioral function to detect unusual targets, which is supported by a top-down functioning of the cholinergic neural system. In contrast, the arousal component of attention may not involve a specific behavioral responsiveness, but it could be necessary for the development of vigilance across time by the bottom-up innervations of the noradrenergic system. In the present study, we describe the behavioral pattern for each component, including the type and size of the associated performance decrement. Future studies linking neuroimaging and behavioral data may contribute to the analysis of the independence of these vigilance components (Posner, 2012b; Posner et al., 2006).

Finally, although we expected no significant differences in the measurement of the classic attentional functions, in both experiments we found a much reduced interference effect in the vertical version of the task, as compared to the horizontal version. We consider that this modulation of the interference effect cannot be entirely explained by the direction of the infrequent target displacement. Previous studies with the 'lateralized ANT task' reported similar interference effects with stimuli presented vertically (i.e., a column of arrows in one or another side of the screen), and stimuli presented horizontally (Asanowicz & Marzecová, 2017; Greene et al., 2008). Thus, we decided to conduct a new study specifically to address this issue (for a reference of the project in Open Science Framework, see https://osf.io/h4tk7). We hypothesized that staying vigilant to the vertical displacement of the target might help to segregate this stimuli from the surrounding arrows in the embedded flanker task, in contrast to the horizontal displacement. Thus, in this study we presented the same stimuli as the standard task used in Experiment 2 of the current study. However, participants had to either respond to only the flanker task (ignoring any other stimuli), or at the same attending and responding with the space bar to the vertical vs. the horizontal displacement of the central arrow. Results showed the typical interference effect (~50 ms) when just solving the flanker task, a smaller effect (~35 ms) when attempting to detect at the same time the vertical displacement, and a larger interference (~100 ms) when attending to the horizontal infrequent displacement (Luna et al., Unpublished results).

In any case, the results obtained here seem to support the idea that the vertical version of the ANTI-Vea task is more appropriate to assess the classic attentional functions. This version shows the typical interactions previously observed in the ANTI task (Callejas et al., 2005, 2004). Moreover, the reduction found in the interference effect has an additional advantage. The indexes of the three classic attentional functions are of a similar size, around 40 ms each, with the ANTI-Vea (vertical version), whereas the index of executive control is at least twice the size of the other indexes in the other versions of the task: the horizontal version, the ANT (J Fan et al., 2002), and the ANTI (Callejas et al., 2004).

Conclusions

The current study presents a new attentional networks test (ANTI-Vea) developed for measuring phasic alertness, orienting and executive control, and their interactions, while assessing both executive and arousal components of vigilance. The executive vigilance decrement was found as an increment in response bias towards a more conservative criterion. On the other hand, the arousal vigilance decrement was observed as a progressive increment of both the mean and the variability of RT, and percentage of lapses. In addition, the vertical version of the task proposed here results easier to perform than the previous horizontal version developed by Roca et al. (2011), as indicated by faster overall RT and fewer errors, together with a great reduction in the interference effect. Therefore, it is expected the ANTI-Vea task would be more useful for studying the functioning of the attentional networks in different populations of interest, such as clinical patients and older adults.

Chapter IV

Experimental Series 2

Disentangling the analytical biases, attentional components, and cognitive loads of the vigilance decrement

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Abstract

The vigilance decrement is a widely-reported phenomenon that reflects the difficulty for sustaining attention over long time periods. Currently, there is an opened-debate concerning whether the vigilance decrement is due to a progressive depletion of the available attentional resources, or the emergency of mind wandering thoughts. In the present study, we contrasted the resources overload and mind wandering hypotheses by examining vigilance in a wide set of cognitive loads (i.e., simple, dual, or triple tasks). Conversely to the predictions anticipated from the resources overload model (the higher the cognitive load, the larger the vigilance decrement), and from the mind wandering account (increasing the cognitive load should enhance the task-engagement and reduce the decrement), performance decreased linearly in the simple and triple tasks, but not in the dual one. We propose that vigilance should be examined considering two dissociated components of this process. In this line, the executive vigilance component, measured as the detection of infrequent signals, showed a decrement modulated by the cognitive loads. Instead, in the arousal vigilance component, conceived as sustaining a fast reaction to stimuli without selecting a specific response, the decrement (measured as reaction time variability) was independent from cognitive loads. Additionally, we provide critical evidence that the executive vigilance decrement is best interpreted as a shift in the response criterion, supporting previous findings that sensitivity loss is biased by a floor effect in the false alarms. We discuss the theoretical and methodological limitations of the resources overload and mind wandering hypotheses regarding the vigilance decrement.

Introduction

Vigilance – i.e., the ability to sustain attention over extended periods of time – has been traditionally studied with simple, monotonous, and intellectually unchallenging behavioral tasks, wherein it is commonly observed a progressive decrement on performance as a function of time on task (Langner & Eickhoff, 2013; Mackworth, 1948; Scerbo, 1998). Nowadays, the leading explanation about the vigilance decrement is based on the assumption that staying vigilant requires great cognitive effort, which is experienced as stressful, so that across time on task there seems to be a depletion of the available attentional resources (R. A. Grier et al., 2003; Warm et al., 2008). Nonetheless, recent theoretical reviews and empirical studies have remarked the imperative need of novel approaches on the assessment of vigilance, to achieve new important objectives that we will try to address in the present study. On the one hand, to dissociate different components of attention through diverse levels of cognitive demands (Roca et al., 2018; Tkachenko & Dinges, 2018). On the other hand, to develop original frameworks that may overcome classic (and limited) explanations about the vigilance decrement as a function of time on task (Thomson, Besner, et al., 2015; Thomson et al., 2016).

The Analytical Biases in the Vigilance Decrement

In behavioral tasks such as the Mackworth Clock Test (MCT; Mackworth, 1948), the Sustained Attention to Response Task (SART; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997), or the Continuous Performance Test (CPT; Conners, 2000), the vigilance decrement is reported as a progressive decline in the correct detection (i.e., hit) of critical infrequent signals. For instance, in the MCT, participants must stay alert to detect the occurrence of an unusual double jump of the clock hand (Mackworth, 1948). Traditionally, by using Signal Detection Theory (SDT) metrics, it has been explained that the decrement on the hits corresponds to a loss in the sensitivity to discriminate the occurrence of critical signals from the remaining noise events, e.g., the regular jump of the clock hand on the MCT (See et al., 1995).

Nevertheless, a recent review and empirical demonstration by Thomson et al. (2016) has pointed out several flaws of classic vigilance tasks to properly determine the potential shifts of SDT metrics across time on task. To start with, simple and monotonous tasks are generally very easy to resolve. As a consequence, in the first period of the task, a ceiling effect on the hit rate is commonly found along with a floor effect on the false alarms (FA) rate, i.e., the incorrect attempts to detect the signals. This is a critical issue because, if FA are on the floor at the beginning of the task, then there is no possibility that the decrement on the hits be accompanied by a similar decrement on the FA, in which case it would reflect a shift in the response bias towards a more conservative criterion, rather than a loss in sensitivity (Thomson et al., 2016).

To test the critical hypothesis that a floor effect on the FA could be masking a shift in the response bias, Thomson et al. (2016) developed a novel paradigm in which the noise events included a low proportions of lure trials, that should be specifically more difficult to discriminate from the signal events than the remaining non-lure trials. Participants had to perform a categorical decision task over serially presented words, staying vigilant to detect only words representing four-legged creatures (e.g., 'squirrel', 10 per block). In the remaining noise events, most of them represented inanimate objects (e.g., 'phone', 80 per block as non-lure trials). Furthermore, and critically, the low proportion of lure trials were words representing non four-legged creatures (e.g., 'canary', 10 per block). As predicted by Thomson et al., in the first task period the FA rate increased importantly (i.e., ~33%) when it was computed considering only the lure trials, in contrast to the computation considering both the lures and non-lures trials (i.e., ~5%). Importantly, the FA computed from the lure trials showed a prominent decrement, and as a consequence, the vigilance decrement was revealed as an increment in the response bias, and not as a loss in the sensitivity (Thomson et al., 2016).

The Theoretical Models about Vigilance

Currently, the most widely accepted account about vigilance is based on the ’resources overload’ perspective, and it has been built over the general agreement – as above-mentioned – that the shifts in performance reflects a drop in the sensitivity rather than in the response willingness (See et al., 1995; Thomson et al., 2016). Based on the assumptions that vigilance tasks are hard to perform, demand a high mental work load, and are very stressful for participants, the sensitivity loss would be, indeed, a result of a progressive depletion of the available attentional resources (R. A. Grier et al., 2003; Warm et al., 2008). In this line, several studies have reported that an increment in the tasks’ cognitive demands would lead to an even larger decrement (Epling et al., 2016; Head & Helton, 2014; Helton & Russell, 2011).

However, along the last two decades, the ‘mind wandering’ account has criticized the putative conception that the attentional resources are just consumed over time, suggesting that resources are rather re-directed from task-relevant thoughts – necessary to solve the external activity – toward internal thoughts unrelated to the task at hand (Smallwood & Schooler, 2006; Stawarczyk & D’Argembeau, 2016; Thomson et al., 2014). From this perspective, the difficulties to sustain attention over prolonged periods of time would be linked to the disengagement of attention, which is supposed unnecessary for solving such monotonous and simple tasks, indeed reported in many studies as highly boring by participants (Danckert & Merrifield, 2016; Robertson et al., 1997; Thomson, Besner, et al., 2015).

Dissociating Vigilance Components and others Attentional Functions

Recently, several studies have raised the importance of assessing vigilance with more complex tasks, including measures from others attentional components, and leaving out the traditional approach of using simple, monotonous, and boring tasks (Roca et al., 2018; Tkachenko & Dinges, 2018; Wickens, Hutchins, Laux, & Sebok, 2015). Indeed, we consider that the classic vigilance tasks could be measuring different components of this process. Whilst the MCT, CPT, or the SART seem to assess an executive component of vigilance, related to the control of responses to select critical signals over noise events across time, other paradigms such as the Psychomotor Vigilance Test (PVT; Lim & Dinges, 2008) seems to measure an arousal component of vigilance, necessary to keep a fast reaction to stimuli without implementing any control over responses. In the typical PVT, participants must stay alert over 10 minutes to stop, as fast as possible and by pressing any available key, a millisecond counter that appears at random intervals from 2 to 10 seconds (Basner & Dinges, 2011). Importantly, participants do not have to be continuously selecting among different response's options and stimuli, as the same simple response is to be given to the only possible stimulus. Therefore, the vigilance decrement is reported as a progressive increment in reaction time (RT) variability and lapses (excessively slow RTs; Lamond et al., 2008; Lamond, Dawson, & Roach, 2005; Loh, Lamond, Dorrian, Roach, & Dawson, 2004).

In order to obtain an independent measure of several attentional functions within a single experimental session, we have recently developed the Attentional Networks Test for Interactions and Vigilance – executive and arousal components (ANTI-Vea; Luna, Marino, Roca, & Lupiáñez, 2018). The procedure of the task is fully described in Luna et al. (2018), and also in the Method of Experiment 1. In short, in the largest proportion of trials (i.e., 60%), participants have to resolve the ANTI task of Callejas, Lupiáñez, and Tudela (2004), a flanker paradigm with visual cues and warning signals, that is useful to assess the classic attentional networks functions: phasic alertness, orienting, and executive control (S. E. Petersen & Posner, 2012; Posner & Petersen, 1990). The executive vigilance task consists in detecting an infrequent vertical displacement of the target (i.e., the central arrow of a five arrow string, vertically displaced in 20% of the trials). In the remaining 20% of trials, participants perform the arousal vigilance task, in which a millisecond counter must be stopped as fast as possible by pressing any key from the keyboard.

With the ANTI-Vea task, Luna et al. (2018) observed the executive vigilance (EV) decrement as an increment in the response bias, and not as a loss in sensitivity, in line with the empirical demonstration by Thomson et al. (2016). Moreover, the arousal vigilance (AV) decrement was observed as a linear increment in the RT variability, as it is usually observed with the PVT (Basner & Dinges, 2011). The usual indices of phasic alertness, orienting, and executive control were also observed, thus proving the task is suitable to measure the classic attentional functions together with the EV and AV components.

The Current Study

In the present research, we aimed at contrasting several predictions derived from the resources overload and mind wandering accounts concerning the vigilance decrement phenomenon, which has been traditionally studied by simple and monotonous behavioral tasks. From the resources overload perspective, the sensitivity loss effect is explained as a consequence of a progressive depletion in the available attentional resources. Thus, it is assumed that more complex tasks should demand a greater amount of resources and lead to a larger decrement across time, in comparison to simple tasks (Warm et al., 2008). Note, however, that this widely-reported effect in sensitivity loss has been recently objected as an analytical problem of simple vigilance tasks, wherein is commonly observed a floor effect in the FA rate (Thomson et al., 2016). On the contrary, the mind wandering account predicts that simple vigilance tasks are low demanding and easy to perform, and thus, more complex tasks could reduce the emergency of task irrelevant thoughts, enhancing the engagement to perform the activity at hand (Smallwood & Schooler, 2006), and therefore reducing the vigilance decrement.

Therefore, with the aim to determine whether the vigilance components could reflect distinct fluctuations over time as a function of the cognitive load of the task, and also to obtain at the same time and within a single session independent measures of several attentional components, we decided to assess the vigilance components with the ANTI-Vea task (Luna et al., 2018). In Experiment 1, we challenged the statement that the vigilance decrement is mainly due to a loss in the sensitivity – as explained by the resources overload model –, by addressing the analytical problem stated by Thomson et al. (2016), which predicts that if FA are not at floor, then it could be observed a considerable shift in the response bias rather than in the sensitivity. In Experiment 2, by using the same methodological approach as in Experiment 1, we reduced the cognitive load of the triple task (ANTI-Vea) in order to assess either just the two vigilance components in a dual task, or each one separately through simple tasks. We hypothesized that, if the vigilance decrement is mainly due to the scarcity of attentional resources across time (as predicted by the resources overload account), the higher the attentional demands (triple > dual > single task), the higher the vigilance decrement should be. From the mind wandering account, instead, it would be expected that a better performance (i.e., reduced vigilance decrement) could be achieved by increasing the task demands, as there would be a higher engagement than when performing a simple task (single > dual > triple task).

Finally, to test the assumed conception that vigilance tasks are subjectively experienced as stressful by participants, we analyzed the self-reported level of mental and physical fatigue at performing tasks with different cognitive loads. If such stressful experience is a consequence of the hard cognitive effort demanded by vigilance tasks, as explained by the resources overload theory, then complex tasks should be more stressful than simple ones (Warm et al., 2008). By contrast, if the stressful experience is due to the monotonous and boring character of traditional simple tasks, as stated by the mind wandering account, then more complex tasks should be perceived as less stressful for participants than simple ones (Smallwood & Schooler, 2006; Thomson, Besner, et al., 2015). Thus, the current study aims to solve several methodological issues regarding the traditional approach in the study of vigilance, which will allow the contrast between the resources depletion and mind wandering hypotheses.

Experiment 1

The main goal for the present experiment was to investigate the mechanism underlying the EV decrement across time on task, for which we analyzed how the FA rate affects the computation of SDT metrics across time. Two specific motivations guided us: (a) to know whether FA tend to increase or decrease with time on task, and (b) whether the increment or decrement in FA across time depends on the FA rate at the beginning of the task. To address these issues, we decided to extend the methodological approach developed by Thomson et al. (2016) in two different versions of the ANTI-Vea, wherein it has already been observed a progressive increment in the response bias (Luna et al., 2018). Based on the standard version of the ANTI-Vea, we designed a similar version in which we included a low proportion of lure trials that we expected to importantly increase the FA rate. Therefore, if the FA rate tends to decrease across time, or at least do not shows a progressive increment, probably the shift on performance will be reflected as a change in the response bias rather than as a loss in sensitivity.

Furthermore, as in Luna et al. (2018), we expected to succeed in measuring the two vigilance components simultaneously. Thus, apart from the hypothesis regarding EV described above, we expected to observe the AV decrement as an increment in the mean and RT variability. Regarding the classic attentional functions, we expected the typical effects usually reported with the ANTI task (Callejas et al., 2004). In particular, for the phasic alertness functioning, we expected to observe faster responses when the stimuli are anticipated by a warning signal. For the orienting functioning, probably the presence of predictive visual cues would benefit the target selection. Last, for the executive control network, we anticipated that the presence of incongruent distractors would impair target selection as compared to congruent distractors.

Method

Participants

A total of 86 healthy volunteers (61 women; age *M* = 22.70, *SD* = 5.54; education years: *M* = 13.95; *SD* = 1.30), all of them with normal or corrected to normal vision, participated in this study. All participants were undergraduate students from the Universidad Nacional de Córdoba, Argentina. In this and the following experiment, participants signed a written informed consent, and completed the session individually. Both experiments were conducted according to the ethical standards of the 1964 Declaration of Helsinki (last update Seoul, 2008), and were part of a larger research project approved by the Universidad de Granada Ethical Committee (175/CEIH/2017).

Participants were randomly assigned to one of two groups, depending on the task version performed. Groups did not differ in age [*t* (84) = -0.32, *p* = .748] or education years [*t* (84) = 1.16, *p* = .251].

Apparatus and stimulus

In both experiments, the assessment of fatigue and experimental tasks were designed and run in E-Prime v2.0 Professional (Psychology Software Tools, Pittsburgh, PA). All stimuli and instructions were drawn in black against a grey background. Responses were registered by pressing one key on a standard QWERTY keyboard. In the analog assessment of fatigue (see the Mental and physical fatigue section for details), the response was collected by clicking the left button of a standard mouse.

Stimuli and timing were the same as in the original ANTI-Vea (Luna et al., 2018): a black fixation cross (~7 pixels -px-), a black asterisk (~13 px), a warning tone (2000 Hz, presented through headphones), a red millisecond down counter (~110 px height each number), and a row of five black arrows (50 px wide x 23 px high each arrow) pointing either leftward or rightward. The horizontal distance between adjacent arrows was set at 63 pixels. In addition, the arrows position was manipulated differently for each task version (see the description of the ANTI-Vea task in the next section for details).

Procedure and design

Self-report questionnaires

In this and the following experiment, prior to the experimental task, participants completed four questionnaires in the following sequence: (a) the Insomnia Severity Index (Bastien et al., 2001), (b) the Cognitive Failures Questionnaire (Broadbent, Cooper, FitzGerald, & Parkes, 1982), (c) the Attentional Control Scale (Derryberry & Reed, 2002), and (d) the Barratt Impulsiveness Scale-11 (Patton, Stanford, & Barratt, 1995). The goal of collecting these data is to correlate self-reported abilities and habits with the performance of the different attentional functions measured with the ANTI-Vea task. Note that, however, this is part of a larger project, so that data of the small *N* of the current experiment will be reported elsewhere when data from a much larger *N* is accumulated.

Mental and physical fatigue

In this and the following experiment, participants self-reported their level of mental and physical fatigue at three different times along the session: a baseline state (i.e., before the instructions and practice), a pre task state (i.e., before starting the experimental task), and a post task state (i.e., at the end of the experimental blocks). The order in which fatigue type (mental vs. physical) was assessed was counterbalanced across participants, and fixed for the three different times for a given participant. Additionally – counterbalanced across participants – one fatigue type was reported in a numeric scale (from 1 –minimum- to 9 –maximum-), and the other type by an analog scale (a visual line from the left –minimum- to right –maximum- of the screen). We decided to assess fatigue by these two different methods in order to compare which one is more reliable when self-reporting the fatigue state. However, as previously mentioned, this goal is also part of a larger research project, and so these analyses will be conducted when data from a much larger *N* is accumulated. Finally, and importantly, as we aimed to analyze the modulations of the mental and physical levels of fatigue as a function of the cognitive demands of the tasks performed in the current two experiments, these data analyses about will be presented following the Discussion of Experiment 2 (see the section Mental and physical fatigue as a function of the cognitive load).

Attentional Networks Test for Interactions and Vigilance – executive and arousal components (ANTI-Vea)

Two different versions of the ANTI-Vea task (Luna et al., 2018) were administered, one per group of participants. In the ANTI-Vea task, three different types of trials may be distinguished: ANTI (60%, in order to assess the classic attentional networks functions and it interactions), executive vigilance (EV, 20%), and arousal vigilance (AV, 20%). The stimuli sequence and procedure for all trials can be observed in Fig. 1, and it is also described in detail in (Luna et al., 2018).

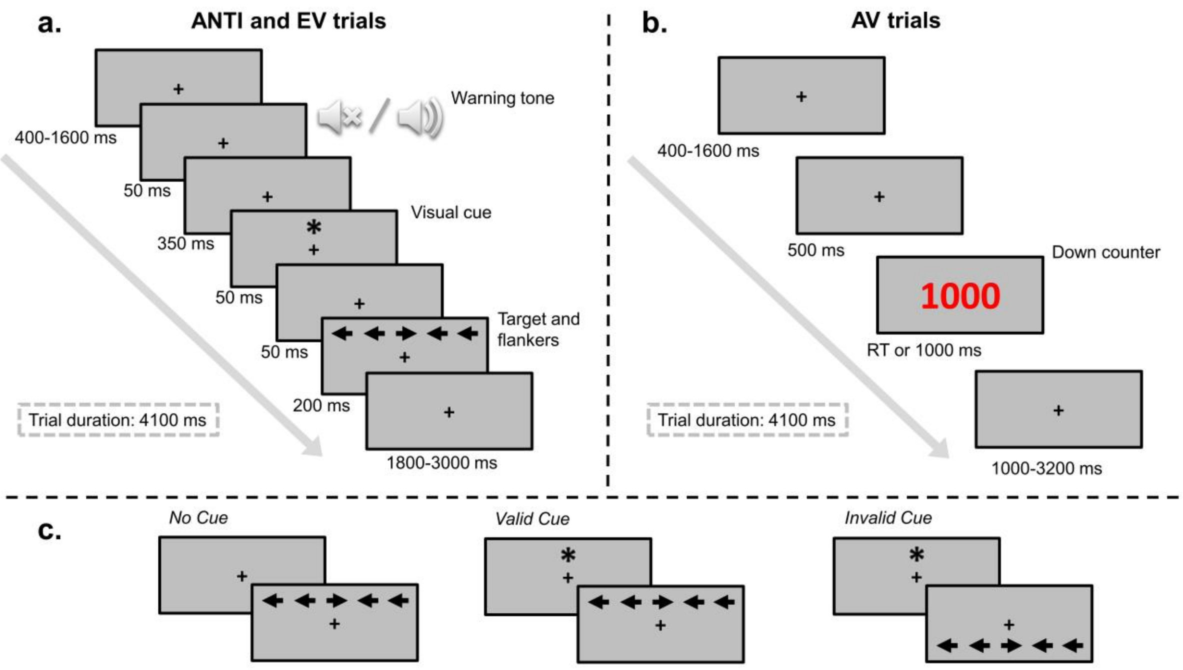

Fig. 1 ANTI-Vea design. Experimental procedure and stimuli sequence of (a) both ANTI and Executive Vigilance (EV) trials and (b) Arousal Vigilance (AV) trials. Responses were allowed until 2000 ms since the target or the down counter presentation. (c) Examples of visual cue conditions.

In short, in ANTI trials, a row of five arrows was presented either above or below the fixation point. Participants had to respond to the direction of the target (central arrow) while ignoring the flanking arrows. To measure executive control, half of the times the target direction was congruent with the flankers' direction, whereas in the other half it was incongruent (examples of congruency are shown in Fig. 2). Previously, and in order to assess phasic alertness functioning, a warning signal was presented in 50% of these trials (tone condition), 500 ms before the arrows appearance (no warning signal was presented in the remaining 50% of the trials; no tone condition). Finally, and for measuring the orienting functioning, a spatially non-predictive visual cue was presented 100 ms before the arrows in 2/3 of the trials (no visual cue was presented in the remaining 1/3 of the trials –no cue condition-

; see examples in Fig. 1). When presented, the cue could be presented at the same location as the target (valid location condition), or at the opposite condition (invalid location condition).

EV trials had the same procedure as ANTI trials (see Fig.1), except that the target was displaced from the central position (see Fig.2). Participants were encouraged to be vigilant to the detection of the displaced targets (i.e., infrequent signals), and respond to it by pressing the space bar (ignoring in this case its direction). Last, in the AV trials, a down counter was presented instead and participants had to stop it as fast as possible, by pressing any key from the keyboard.

The only difference between the two task versions was the possible positions for target and flankers on each trial. In the standard version, a random variability of ±2 px was established for the horizontal and vertical position of the arrows, both in the ANTI (for target and flankers) and EV (only for flankers) trials. This variability on the arrows position aimed to make more difficult to detect the larger and fixed displacement of the target (8 px, either up or down) in the EV trials (see examples in Fig. 2).

On the other hand, in the lure version, the arrows position was set differently, in order to design a vigilance task similar to the one proposed by Thomson et al. (2016). The ±2 px noise was eliminated so that flankers arrows appeared in a fixed position, for both ANTI and EV trials. However, in the ANTI trials, there was 1/3 of lure trials where the target had a smaller and fixed displacement (4 px, either up or down), whilst in the remaining 2/3 of trials it appeared fixed in the center of the row of arrows, without any displacement. These lure trials aimed to make more difficult the detection of the target in EV trials, in which the displacement was larger and also fixed (8 px, as in the standard version), and more importantly, to increase the FA rate on those lure trials.

As a result of the different possible positions of target and flankers, some ANTI trials (i.e., the noise distribution, in terms of SDT) were easier than others to make a correct rejection of the infrequent signal. Fig. 2 represents this difference for both task versions. In the lure version, it was easier to respond as a correct rejection when the target was fixed and centered. In the lure trials, instead, due to the small displacement, it resulted more difficult to make a correct rejection, and so it was more probable to commit a FA.

Moreover, in the standard version, we attempted to categorize off-line the ANTI trials in a way similar to the lure task. To accomplish this goal, the distance (in the vertical axis) between the target and the most separated adjacent flanker was calculated (maximum distance). This distance could be in a range from 0 px (e.g., the target and both adjacent flankers in the same vertical position) to 4 px (e.g., the target 2 px displaced in one direction, and one of the adjacent flankers displaced 2 px in the opposite direction). Then, in those trials where this maximum distance was between 0 and 2 px, we assumed that it was easier to make a correct rejection of the infrequent signal. Instead, in the trials where this distance was 3 or 4 px (i.e., similar to the lure trials), it would be probably more difficult to make a correct rejection, and so more probable to commit a FA. This categorization of the trials in the noise distribution resulted crucial to analyze then the executive vigilance decrement (see the Data Analyses of Experiment 1 for details).

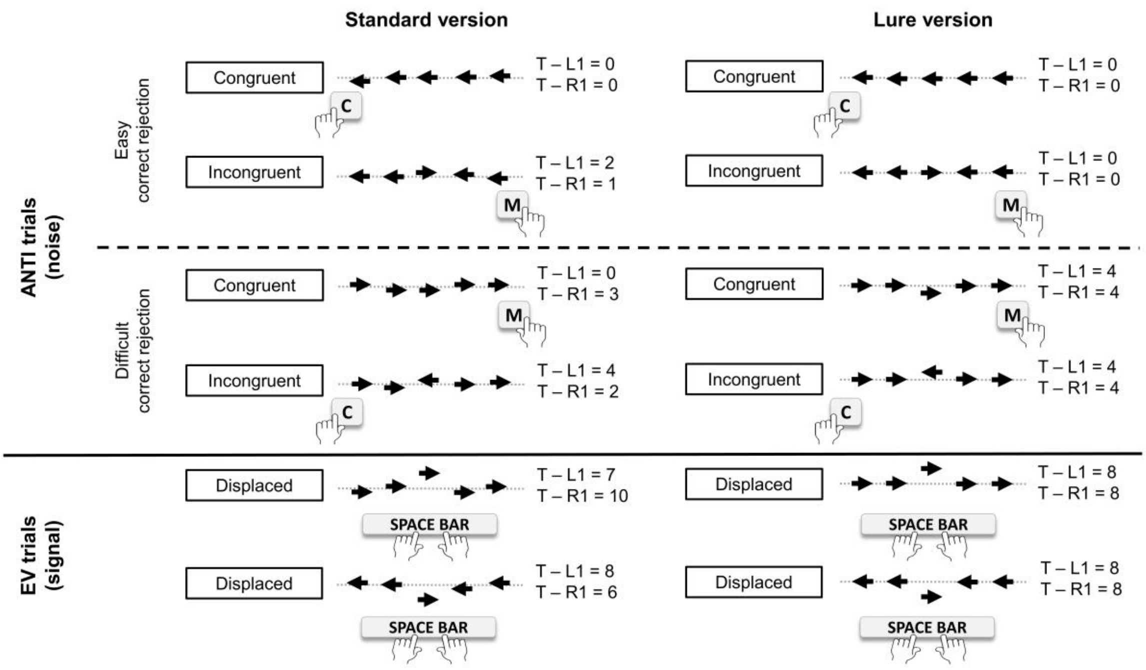

Fig. 2 Target and distractors positions in the ANTI-Vea standard and lure task version. The dotted gray line was not presented in the screen, and it represents the central height for arrows in the vertical axis for both above or below the fixation point. Subtractions on the right of each example show the distance in pixels between the target (T) and the immediate left (L1) or right (R1) distractor. The correct answer for the each example it is shown below the arrows

Finally, before starting the experimental task, participants received specific instructions for each type of trial and performed several practice blocks with visual feedback. Further details on the sequence of instructions and practice are described in Luna et al. (2018). The experimental section of the task included six blocks of 80 randomly presented trials (48 ANTI, 16 EV, and 16 AV), without any pause or feedback. The 48 ANTI trials had the following factorial design: 2 (warning signal: no tone/tone) x 3 (visual cue: invalid/no cue/valid) x 2 (congruency: congruent/incongruent) x 2 (target direction: left/right) x 2 (arrows position with respect to the fixation point: above/below). The two lasts factors were not considered in posterior analyses. In the lure version, 16 ANTI trials were randomly selected as the lure trials per block. Last, for EV trials one factor was added to the design: displacement direction (up/down). The 16 EV trials per block were randomly selected from the 96 possible combinations.

Data analyses

In this and the following experiment, analyses were performed in Statistica 8.0 (StatSoft Inc.), and figures were made with Matplotlib 3.0.0 (Hunter, 2007). First, and following the criteria from Luna et al. (2018), seven participants were excluded from further analyses, due either to an extreme average RT (2.5 *SD* above the group average), or to a performance unusually low for the typical ANTI task (i.e., equal or higher than 25% of errors). For the next analyses, 40 participants were included in the standard task group, and 39 in the lure one. Significance level was established at .05.

In the ANTI trials, RT analyses excluded incorrect responses (7.79%), and with an extreme RT (0.61%, i.e., faster than 200 or slower than 1500 ms). Then, two repeated measures ANOVAs were conducted, one for RT and another for the percentage of errors, including warning signal (no tone/tone), visual cue (invalid/no cue/valid), and congruency (congruent/incongruent) as within-participants factors, and task version (standard/lure) as a between-participants factor.

In order to analyze the vigilance decrement across time on task, EV and AV measures were calculated per block of trials. For EV trials, warning tone, visual cue, and congruency, were not considered for analysis, with data being collapsed across these variables. Hits were computed in one single way from the signal distribution (i.e., EV trials), as the proportion of infrequent signals (i.e., larger displaced targets) correctly detected. FA were computed as the proportion of frequent stimuli (i.e., ANTI trials) detected as infrequent signals. The ‘total’ computation of FA included all trials from the noise distribution (i.e., the whole set of ANTI trials). In addition, we computed a ‘corrected’ FA rate selecting only those trials where it was more difficult to make a correct rejection of the infrequent signal, and so more probable to commit a FA (see description in the above section, and in Fig. 2).

Next, non-parametric indexes of sensitivity (A’) and response bias (B’’) were obtained (J. B. Grier, 1971). Both indexes were computed including the ‘total’ and ‘corrected’ FA rate. The advantages of using non-parametric over classic parametric indexes (d’ for sensitivity and β for response bias) can be reviewed in multiple studies (e.g., Stanislaw & Todorov, 1999; Thomson, Besner, & Smilek, 2016). Additionally, we obtained the mean and SD of RT on hits per block (0.98% trials excluded for extreme RT). Then, nine repeated measures ANOVAs were conducted separately including task blocks (6 levels) as within-participants factors, and task version (standard/lure) as a between-participants factor, one for each dependent variable: hits, the ‘total’ and ‘corrected’ computation for FA, A’ (sensitivity) and B” (response bias), and the mean and SD of RT on hits.

For the AV trials, mean and SD of RT, and the percentage of lapses (i.e., late responses to the down counter) were computed per block. Usually, mean RT in the PVT studies is ~250 ms (e.g., see Basner, Mollicone, & Dinges, 2011; Blatter et al., 2006; Drummond et al., 2005; Lee, Bardwell, Ancoli-Israel, & Dimsdale, 2010; Lim & Dinges, 2008; Loh, Lamond, Dorrian, Roach, & Dawson, 2004), and so lapses are considered as responses equal or larger than 500 ms. However, in the present study, mean RT on AV trials was ~470 ms in both task versions (probably due to the inclusion of ANTI and EV trials along with the down counter presentation). Therefore, the threshold for lapses was set as higher than 600 ms, as in the previous study conducted with the ANTI-Vea task (Luna et al., 2018). Then, three repeated measures ANOVAs were conducted separately, including task blocks (6 levels) as a within-participants factor, and task version (standard/lure) as a between-participants factor, one for each dependent variable: mean RT, SD of RT, and percentage of lapses.

Results

Phasic alertness, orienting, and executive control

Mean RT and errors for ANTI trials conditions are shown in Table 1.

Table 1. Mean correct RT (ms) and percentage of errors for the ANTI conditions in both ANTI-Vea task versions as a function of warning signal (no tone/tone), visual cue (invalid/no cue/valid), and congruency congruent/incongruent). SD are shown between parentheses.

		No tone			Tone		
		Invalid	No cue	Valid	Invalid	No cue	Valid
Reaction Time							
Standard	Congruent	671 (110)	676 (108)	643 (127)	656 (100)	623 (94)	612 (103)
	Incongruent	722 (113)	711 (112)	685 (105)	713 (106)	677 (107)	663 (122)
Lure	Congruent	653 (98)	655 (102)	632 (104)	642 (106)	614 (90)	602 (94)
	Incongruent	700 (99)	685 (93)	666 (104)	688 (101)	660 (107)	636 (98)
Errors							
Standard	Congruent	8.85 (8.65)	6.14 (6.18)	8.22 (7.51)	7.18 (7.72)	5.10 (4.66)	7.08 (7.25)
	Incongruent	7.08 (6.12)	6.56 (5.88)	8.43 (7.33)	4.58 (5.32)	3.95 (4.61)	5.93 (5.73)
Lure	Congruent	8.65 (8.57)	9.93 (7.74)	8.76 (7.98)	7.15 (6.61)	6.94 (7.60)	10.68 (9.87)
	Incongruent	8.44 (6.79)	8.76 (7.87)	10.47 (8.54)	8.11 (7.58)	9.82 (9.81)	10.47 (9.31)

Reaction time

Significant main effects were found for the three within-participants factors: warning signal [*F* (1, 77) = 85.21, *p* < .001, η_p^2 = .53], visual cue [*F* (2, 154) = 94.08, *p* < .001, η_p^2 = .55], and congruency [*F* (1, 77) = 143.81, *p* < .001, η_p^2 = .65]. Task version effect was not significant [*F* (1, 77) = 0.69, *p* = .407, η_p^2 = .01], with similar overall RT for the standard (*M* = 671 ms; *SD* = 102) and the lure version (*M* = 653 ms; *SD* = 95).

Only the interaction between warning signal and visual cue was significant [*F* (2, 154) = 12.44, *p* < .001, η_p^2 = .14]. The remaining interactions between the attentional networks were marginal: Warning signal x Congruency [*F* (1, 77) = 3.13, *p* = .081, η_p^2 = .04], and Visual cue x Congruency [*F* (2, 154) = 2.41, *p* = .093, η_p^2 = .03]. The three way interaction between the three within-participants factors was far from significance [*F* (2, 154) = 1.15, *p* = .319, η_p^2 = .01]. Task version did not modulate any other variable or their interactions (all *F*s < 1.40, *p* > .240).

Errors

Significant main effects were found for both the warning signal [*F* (1, 77) = 6.68, *p* = .011, η_p^2 = .08] and visual cue [*F* (2, 154) = 6.79, *p* = .001, η_p^2 = .08], but not for congruency [*F* (1, 77) = 0.13, *p* = .721, η_p^2 = .01]. In addition, the main effect of task version was significant [*F* (1, 77) = 4.93, *p* = .029, η_p^2 = .06], with lower overall percentage of errors for the standard (*M* = 6.60%; *SD* = 4.02) than for the lure version (*M* = 9.02%; *SD* = 5.56).

The interactions between the within-participant factors were all far from significance (all *F*s < 1.50, *p* > .230). Task version only modulated visual cue [*F* (2, 154) = 3.16, *p* = .045, η_p^2 = .04]. In the standard version, the error percentage was smaller in the no cue (*M* = 5.44%, *SD* = 3.66), than in the invalid (*M* = 6.92%, *SD* = 5.22) and valid (*M* = 7.42%, *SD* = 4.97) trials. In the lure version, instead, errors percentage was smaller in the invalid (*M* = 8.09%, *SD* = 5.46), than in the no cue (*M* = 8.87%, *SD* = 5.56) and valid (*M* = 10.09%, *SD* = 6.94) trials.

Executive vigilance decrement

Mean and RT variability

Mean RT on hits did not change significantly across blocks [*F* (5, 375) = 1.55, *p* = .173, η_p^2 = .02]. However, there was a significant increment in the SD of RT across blocks [*F* (5, 375) = 2.36, *p* = .039, η_p^2 = .03]. Task version did not show a main effect (mean RT [*F* (1, 75) = 2.55, *p* = .114, η_p^2 = .03], and SD of RT [*F* (1, 75) = 0.36, *p* = .548, η_p^2 = .01]), neither modulated the effect of blocks with any dependent variable (all *F*s < 1). The overall RT measures were similar for both tasks (standard: *M* = 743 ms, *SD* = 139; lure: *M* = 770 ms, *SD* = 144).

Hits

As it can be observed in Fig. 3, a significant decrement across blocks was observed on hits [*F* (5, 385) = 4.16, *p* = .001, η_p^2 = .05], together with a main effect of task version [*F* (1, 77) = 6.59, *p* = .012, η_p^2 = .08]. The overall hits rate was higher in the standard (*M* = 81.77%, *SD* = 11.76) than in the lure version (*M* = 71.95%, *SD* = 21.05).

Importantly, task version did not modulate hits rate across blocks [*F* (5, 385) = 0.34, *p* = .885, η_p^2 = .01]. Post-hoc comparisons confirmed that the linear component of task versions did not differ when it was contrasted from one another [*F* (1, 77) = 0.35, *p* = .555, η_p^2 = .01]. However, when task versions were analyzed separately, the linear component in the standard version was significant [*F* (1, 77) = 7.02, *p* = .009, η_p^2 = .08], whilst in the lure version was marginal [*F* (1, 77) = 3.18, *p* = .078, η_p^2 = .04].

False alarms

As can also be observed in Fig. 3, the FA rate computed from all trials did not change significantly across blocks [*F* (5, 385) = 1.42, *p* = .214, η_p^2 = .02], and was not modulated by task version [*F* (5, 385) = 0.71, *p* = .618, η_p^2 = .01]. However, there was a significant main effect for task version [*F* (1, 77) = 8.60, *p* = .004, η_p^2 = .10], with a smaller overall FA rate from all trials in the standard (*M* = 4.74%, *SD* = 2.85) than in the lure version (*M* = 7.42%, *SD* = 5.00).

However, as expected and observed in Fig. 3, the corrected computation showed an important increment in the FA rate. The main effect of task version [*F* (1, 77) = 22.59, *p* < .001,

η_p^2 = .23] resulted larger than in the computation from all trials, with much fewer FA commission in the standard (corrected *M* = 8.53%, *SD* = 5.35) than in the lure version (corrected *M* = 19.50%, *SD* = 13.86). Nevertheless, despite the important increment in the corrected FA rate, no main effect of blocks was observed [*F* (5, 385) = 1.24, *p* = .291, η_p^2 = .02], which was neither modulated by task version [*F* (5, 385) = 0.39, *p* = .854, η_p^2 = .01]. Post-hoc comparisons confirmed that the linear component for each task version separately was not significant (both *F*s < 1.20, *p* > .283).

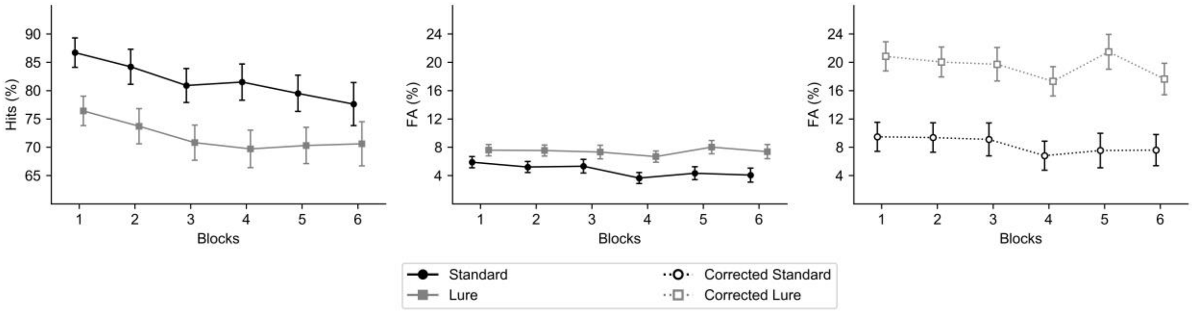

Fig. 3 Hits and false alarms (FA) across time on task. FA rate computed with all trials is shown in the central graph, and the corrected computation on the right graph. Bars represents SE.

Sensitivity

As can be observed in Fig. 4, A’ computed from all trials tended to decrease across blocks [*F* (5, 385) = 2.55, *p* = .027, η_p^2 = .03], independently of task version [*F* (5, 385) = 0.27, *p* = .929, η_p^2 = .01]. In addition, the main effect of task version was significant [*F* (1, 77) = 15.08, *p* < .001, η_p^2 = .16], with a higher overall A’ in the standard (A’ = .94) than in the lure version (A’ = .90).

The corrected computation of A’ (i.e., including only the corrected FA rate) showed an even larger main effect of task version than in the computation from all trials [*F* (5, 385) = 59.37, *p* < .001, η_p^2 = .44], with a higher overall A’ for the standard (A’ corrected = .93) than for the lure version (A’ corrected = .86). Most important, as it can be seen in the same Fig. 4, the corrected computation of A’ demonstrated that there was no-change across blocks [F (5, 385) = 0.86, p = .505, η_p^2 = .01], again independently of task version [F (5, 385) = 0.27, p = .927, η_p^2 = .01]. Post-hoc comparisons for corrected A’ confirmed that the linear component was not significant, neither for the standard [F (1, 77) = 1.48, p = .227, η_p^2 = .02] nor for the lure version [F (1, 77) = 1.35, p = .247, η_p^2 = .02].

Response bias

As can be observed in Fig. 4, B” computed from all trials showed an increment across blocks [F (5, 385) = 2.66, p = .022, η_p^2 = .03]. No main effect of task version [F (5, 385) = 0.01, p = .99, η_p^2 = .01], or Task version x Blocks interaction [F (5, 385) = 1.79, p = .114, η_p^2 = .02] were observed. The overall B” computed from total trials was similar for both the standard (B” = .41) and the lure version (B” = .35).

As can also be observed in Fig. 4, the corrected computation of B” (i.e., including only the corrected FA rate) confirmed the increment across blocks [F (5, 385) = 3.03, p = .010, η_p^2 = .04]. Again, this increment was not modulated by task version [F (5, 385) = 1.52, p = .181, η_p^2 = .02]. The main effect of task version was not significant [F (1, 77) = 0.74, p = .392, η_p^2 = .01], with a similar overall performance for the standard (B” corrected = .23) and the lure version (B” corrected = .09). Nevertheless, as shown in the same Fig. 4, the increment in the corrected B” seems to be qualitatively different between task versions. Post-hoc comparisons showed no task differences in the linear component [F (1, 77) = 1.30, p = .258, η_p^2 = .02]. However, when task versions were analyzed separately, the linear increment was significant for the standard [F (1, 77) = 7.81, p = .006, η_p^2 = .10], but not for the lure version [F (1, 77) = 1.34, p = .250, η_p^2 = .02].

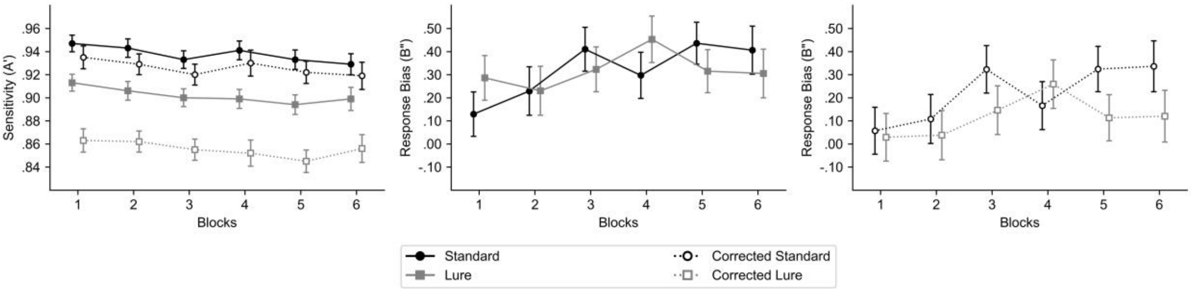

Fig. 4 Sensitivity and response bias over time on task. Both computations of sensitivity (i.e., with all or only the corrected trials) are represented in the right graph. Response bias computed with al trials is shown in the central graph, and the corrected computation on the right graph. Bars represents SE.

Arousal vigilance decrement

Mean and RT Variability, and lapses percentage

Fig.5 shows the increment across blocks for mean RT [*F* (5, 385) = 2.51, *p* = .029, η_p^2 = .03], SD of RT [*F* (5, 385) = 4.03, *p* = .001, η_p^2 = .05], and lapses percentage [*F* (5, 385) = 2.36, *p* = .029, η_p^2 = .03]. None of these increments was modulated by task version (all *F*s < 1). Considering the two task versions together, post-hoc comparisons confirmed a significant linear increment across blocks for both SD of RT [*F* (1, 77) = 8.95, *p* = .003, η_p^2 = .10] and lapses percentage [*F* (1, 77) = 4.60, *p* = .035, η_p^2 = .06], and a marginal increment for mean RT [*F* (1, 77) = 3.94, *p* = .050, η_p^2 = .05].

In general, task versions did not differ significantly for any dependent variable in AV (all *F*s < 1.10, p > .290): mean RT (standard overall = 475 ms; lure overall = 471 ms), SD of RT (standard overall = 82; lure overall = 79) and lapses (standard overall *M* = 10.91%, *SD* = 16.19; lure overall *M* = 7.59%, *SD* = 11.67).

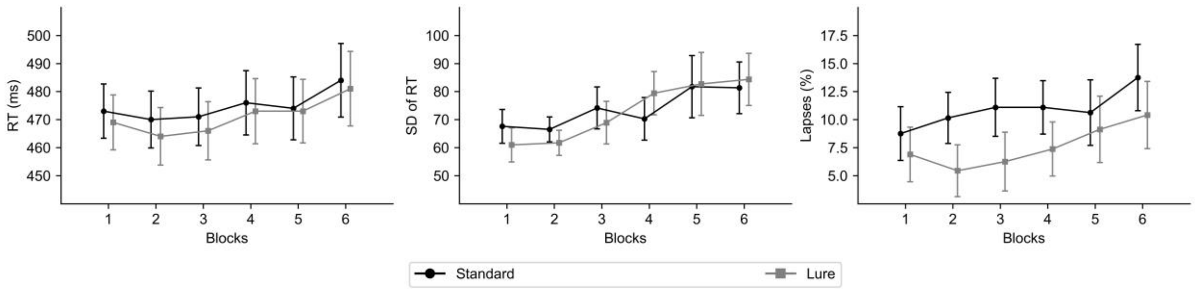

Fig. 5 Arousal vigilance decrement in both ANTI-Vea task versions. Mean RT (left graph), SD of RT (center graph) and lapses percentage (right graph). Bars errors represents SE.

Discussion

In this first experiment, we aimed at replicating the findings reported in the study of Thomson et al. (2016), wherein it was demonstrated that, when the FA are not at floor, the EV decrement is best interpreted as an increment in the response bias and not as a loss in the sensitivity. To this end, we compared two versions of the ANTI-Vea task: the standard one, in which we have previously observed a progressive increment in the response willingness (Luna et al., 2018), and the lure version, based on the paradigm developed by Thomson et al., in which we expected that the lure trials could increase importantly the overall FA rate. Thus, we expected to prove that even if it is observed a considerable rate of FA in the first period of the task, then FA does not tend to increase across time, and so it is more unlikely to observe a relevant drop in the sensitivity.

As expected, in both task versions the FA rate was higher when it was computed only from the corrected trials than from all the noise events, confirming that the lure trials are the most difficult to discriminate from the signal ones. Moreover, as also predicted and in line with Thomson et al. (2016), the overall FA rate was quite higher in the lure task version than in the standard one. However, even though in the lure version it was observed a considerable FA rate on the first period of the task (i.e., a ~22% in the corrected computation), neither in the standard nor in the lure task it was found a significant shift in this measure across blocks. Importantly, the sensitivity loss was found only when it was computed considering FA from all trials, whereas this effect was not observed considering the corrected FA rate, similar to the results obtained by Thomson et al. Therefore, the relevant drop observed in the hits here was accompanied by a non-change in the corrected computation of FA across time, thus leading only to a relevant increment in the response bias.

It is worth mentioning that recently, the study of Thomson and et al. (2016) received several critics by Fraulini, Hancock, Neigel, Claypoole, and Szalma (2017). These authors questioned the analytical methods carried out to obtain SDT metrics, as in the experimental paradigm under consideration, the non-lure trials could be rather considered as an independent distribution of neutral and distracters trials, than as the largest proportion of the noise events. Moreover, Fraulini et al. (2017) pointed out that the vigilance task was performed online and outside the lab, without controlling the experimental context. Notwithstanding, Thomson et al. results were replicated when these two main concerns were controlled (Claypoole et al., 2018).

Furthermore, regarding the reliability to assess the vigilance decrement online and outside the lab, we have addressed this issue in a study with a large sample (N = 617), wherein participants either performed the standard version of the ANTI-Vea task in the lab, or by an online version (https://www.ugr.es/~neurocog/Sitio_web/ANTI/) at their own home (Luna, Roca, Martín-Arévalo, & Lupiáñez, 2019). In both task versions, the split-half reliability indices (corrected by the Spearman-Brown prophecy) were higher than .75 for both the EV and AV measures. Most importantly, it was found a relevant linear increment in the response bias, which was not modulated by the version (lab vs. online). Regarding the shifts in sensitivity, we followed the critical examination proposed by Thomson et al. (2016), and analyzed this effect according to the FA rate observed at the beginning of the task. Thus, the loss in sensitivity [F (5, 1275) = 29.93, $p < .001$, $\eta_p^2 = .10$] was observed only when FA are at floor levels (i.e., equal or lower than 5%) in the first block, but there was no change at all [F (5, 1670) = 1.49, p = .190, η_p^2 = .01] when FA are higher than 5% in the first block.

Lastly, although we expected the lure version as the most suitable task to assess the EV decrement, the standard version seems to be the easiest to be solved, and the most sensitive to measure the two vigilance components along with the classic attentional networks functions at the same time. For instance, in the standard version we observed a higher hits rate and a more linear increment in the response bias than in the lure task. In the ANTI trials, participants also committed fewer errors in the standard than in the lure version. In line with the pattern observed in the study of Luna et al. (2018), here we replicated the same main effects and interactions usually observed by using the ANTI task (Callejas et al., 2004), and the decrement in the AV component as commonly reported in tasks like the PVT (Basner & Dinges, 2011).

In summary, in this first experiment, wherein we applied the analytical method proposed by Thomson et al. (2016), the EV decrement was observed as an increment in the response bias rather than as a loss in sensitivity, replicating recent findings with the ANTI-Vea task (Luna et al., 2018). Although these results are in contrast with the traditional findings reported in the vigilance literature (Helton & Russell, 2017; See et al., 1995; Warm et al., 2008), they are, instead, in line with recent studies using a much simpler and repetitive task than the ANTI-Vea (Claypoole et al., 2018; Thomson et al., 2016). Thus, in order to elucidate this contradictory pattern of findings regarding the vigilance decrement in simple and repetitive tasks, we decided to conduct the Experiment 2, wherein vigilance was also measured by less demanding tasks than the ANTI-Vea. We expect that, by assessing vigilance through a wide range of cognitive loads, and also by examining the self-reported level of mental and physical fatigue when performing each task, we would be able to disentangle whether the predictions stated by the resources overload and mind wandering accounts are appropriate or not to explain the vigilance decrement phenomenon.

Experiment 2

In this second experiment, in order to further test predictions derived from the resource overload (Warm et al., 2008) and mind wandering (Smallwood & Schooler, 2006) accounts, we analyzed the vigilance decrement through diverse levels of cognitive loads. Therefore, both the EV and AV components were assessed either individually (i.e., as in the MCT or the PVT, respectively) or simultaneously (i.e., in a dual vigilance task). To compare these results with those of Experiment 1, the simple and dual vigilance tasks were designed following the procedure of the standard version of the ANTI-Vea task, which seemed to work better than the lure one. Again, and in order to avoid that a floor effect on the FA rate masks a shift in the response bias, we decided to compute SDT metrics considering all or only the corrected trials from the noise events.

In particular, and according to the resources overload model, in a simple EV task the decrement should be observed as a progressive loss in the sensitivity, and not as a shift in the response bias (Helton & Russell, 2017; See et al., 1995). Furthermore, as the cognitive load of the task increases, there should be a larger depletion of the available resources (Helton & Russell, 2011). Thus, it is probable that a larger decrement would be observed with the dual task than with a simple task, although smaller than the one observed with the ANTI-Vea task. Besides, it is also probable that participants would experience a larger mental fatigue when performing tasks with a higher cognitive load than with a simple task.

From the mind wandering perspective, on the contrary, if the task demands a higher level of cognitive load, then it could increases the engagement necessary to maintain the attentional focus on the external activity, thus reducing the emergence of task-unrelated-thoughts and improving performance over time. Therefore, it would be expected to find a smaller decrement in the dual task than in the simple tasks. Finally, regarding the individual assessment of the AV component, we anticipated to find a faster overall RT and a larger decrement, as it is usually observed with the PVT (Basner & Dinges, 2011), than when performing a more demanding activity, like the dual task or the ANTI-Vea.

Method

Participants

A total of 96 healthy volunteers (78 women; age *M* = 19.92, *SD* =2.11; education years *M* = 14.04; *SD* = 0.77) participated in this study. All participants were undergraduate students from the University of Granada, Spain, who gave their written informed consent and were compensated for their participation with course credits (0.1/hour). The sample was divided in four groups by counter-balance selection, according to the vigilance task resolved in the session. Note that groups did not differ in age or education years (both *F*s < 1).

Apparatus and stimulus

Stimuli were the same as in the ANTI-Vea (standard version) administered in Experiment 1. The single difference between vigilance tasks was the correct responses expected for each type of trials (see the next section for details).

Procedure and design

In the different vigilance tasks administered here, the ANTI trials (i.e., 60%) were presented as in the previous experiment, but participants never had to respond to the direction of the central arrow in those trials (i.e., they were just the noise distribution for the main EV task). Participants were instructed differently to resolve one or both vigilance tasks of the ANTI-Vea (standard version). In the four tasks, the number and proportion of trials for the final practice block (without visual feedback), and the experimental section, were the same as in Experiment 1.

Executive vigilance - go for signal task (EV go)

This was a vigilance task similar to the MCT (Mackworth, 1948) and the one developed by Thomson et al. (2016), wherein participants should execute the response to the infrequent stimuli (i.e., signal) and inhibit it to the frequent ones (i.e., noise). Therefore, in the EV trials the correct answer was to press the space bar, whilst in the ANTI trials no key should be pressed. A practice block of 32 randomized trials (16 ANTI and 16 EV) was given, with visual feedback. In the next instructions, participants were told that sometimes a red down counter could appear, and a visual example was given. In these trials, the correct answer was to wait until the down counter finished, without pressing any key. After that, a second practice block of 48 randomized trials (16 ANTI, 16 EV, and 16 AV) was given, also with visual feedback.

Executive vigilance - no go for signal task (EV no go)

Contrary to the task descripted above, participants were instructed to perform the EV task as some typical vigilance tasks such as the SART (Robertson et al., 1997) or the CPT (Conners, 2000). In the ANTI trials (i.e., noise), the correct answer was to press the space bar, whilst in the EV trials (i.e., signal, and also in the AV trials) no key should be pressed. The instructions and practice blocks structure were the same as in the EV go task.

Arousal vigilance task (AV)

Participants should just resolve the AV trials, like in the PVT task (Lim & Dinges, 2008). Whenever the down counter appeared on the screen, the space bar should be pressed as fast as possible (although any key was allowed to be pressed). A first practice block including only 16 AV trials was completed, with visual feedback. Next, it was mentioned that sometimes a row of five arrows could appear on the screen, and no key should be pressed on these trials (i.e., both ANTI and EV). After that, a second practice block with visual feedback was given, including 48 randomized trials (16 ANTI, 16 EV, and 16 AV).

Arousal and executive (go for signal) vigilance task (AV – EV go)

This was a dual vigilance task, wherein participants should resolve the EV (go for signal) and AV task simultaneously. For both EV and AV trials, the space bar should be pressed as correct response, whereas no key was to be pressed for the ANTI trials. First, the instructions detailed previously to resolve the EV go task were given, followed by a practice block of 32 randomized trials (16 ANTI and 16 EV) with visual feedback. Next, instructions for the AV task were presented, with a second practice block of 48 randomized trials (16 ANTI, 16 EV, and 16 AV), with visual feedback.

Data analyses

For the following analyses, three participants were excluded: two of them for having a chance performance (i.e., ~50% of hits or FA), and another participant due to technical issues (i.e., responses were collected only in the first block of trials). Then, final groups were conformed as follows: EV go (N = 23), EV no go (N = 22), AV – EV go (N = 24), and AV (N = 24). For EV, RT analyses excluded trials with incorrect response (8.36%) and those with RT lower than 200 or higher than 1500 ms (0.36%). We performed the same analyses as in Experiment 1, both for EV and AV measures. SDT metrics were computed separately including all and only corrected trials, following the criteria for the standard version in Experiment 1.

Results

Executive vigilance decrement

Mean and RT variability

RT on hits could be analyzed only in the EV go and AV – EV go tasks. An increment across blocks was observed for both the mean [F (5, 225) = 6.36, p < .001, η_p^2 = .12] and the SD of RT [F (5, 225) = 4.71, p < .001, η_p^2 = .09]. The main effect of task version was not significant for any dependent variable (both *F*s < 1), neither did it modulate any increment (both *F*s < 1). Overall RT measures were similar for both task versions (EV go: *M* = 582 ms, *SD* = 129; AV – EV go: *M* = 566 ms, *SD* = 137). Moreover, the increment across blocks showed a relevant linear trend both for mean [*F* (1, 45) = 13.15, *p* < .001, η_p^2 = .23], and SD of RT: [*F* (1, 45) = 16.11, *p* < .001, η_p^2 = .26], that was not modulated by task version (mean and SD of RT: both *Fs*<1).

Hits

A significant decrement was observed on hits rate across blocks [*F* (5, 330) = 6.97, *p* < .001, η_p^2 = .10]. In addition, a main effect for Task version was observed [*F* (2, 66) = 3.23, *p* = .045, η_p^2 = .09]. The overall Hits rate was higher for the dual vigilance task (AV – EV go *M* = 93.45%, *SD* = 5.90), than for both single tasks (EV go *M* = 89.76%, *SD* = 6.63; EV no go *M* = 88.45%, *SD* = 8.23).

More importantly, as can be observed in Fig. 6, the effect of blocks was significantly modulated by the task version [*F* (10, 330) = 2.18, *p* = .018, η_p^2 = .06], so that hits rate seems to decrease linearly for both single tasks (EV go and EV no go: [*F* (1, 66) = 29.76, *p* < .001, η_p^2 = .31]), whereas in the dual task (AV – EV go: *F*<1) it seems to be more stable across blocks. Post-hoc comparisons confirmed that the linear component was not different from one single task to another [*F* (1, 66) = 2.30, *p* = .133, η_p^2 = .01]. However, the linear decrement resulted significantly different when both single tasks were compared together against the dual vigilance task [*F* (1, 66) = 9.94, *p* = .002, η_p^2 = .13].

False alarms

As can be observed in Fig.6, FA rate computed from all trials did not change across blocks [*F* (5, 330) = 1.12, *p* = .349, η_p^2 = .02]. The overall FA rate was smaller in both single tasks (EV go *M* = 7.91%, *SD* = 7.11; EV no go *M* = 9.19%, *SD* = 9.05) than in the dual vigilance task (AV – EV go *M* = 12.38%, *SD* = 10.07), although this difference was not significant [*F* (2, 66) = 1.60, p = .210, η_p^2 = .05]. In addition, Task version did not modulated FA rate across blocks [*F* (10, 330) = 0.58, p = .828, η_p^2 = .02].

The corrected computation of FA showed, as can be observed in Fig. 6, a marginal tendency to decrease across blocks [*F* (5, 330) = 2.00, p = .078, η_p^2 = .03], which was not modulated by task version [*F* (10, 330) = 0.78, p = .643, η_p^2 = .02]. As expected, the corrected overall FA rate increased importantly compared to the computation from all trials, for the EV go (*M* = 13.26%, *SD* = 11.34), EV no go (*M* = 15.12%, *SD* = 11.99), and AV – EV go task version (*M* = 19.36%, *SD* = 13.21). However, the overall differences between task versions were far from significance again [*F* (2, 66) = 1.52, p = .226, η_p^2 = .04]. Post-hoc comparisons revealed that no task version showed a significantly different linear change when it was contrasted with the other tasks (all *F*s < 1).

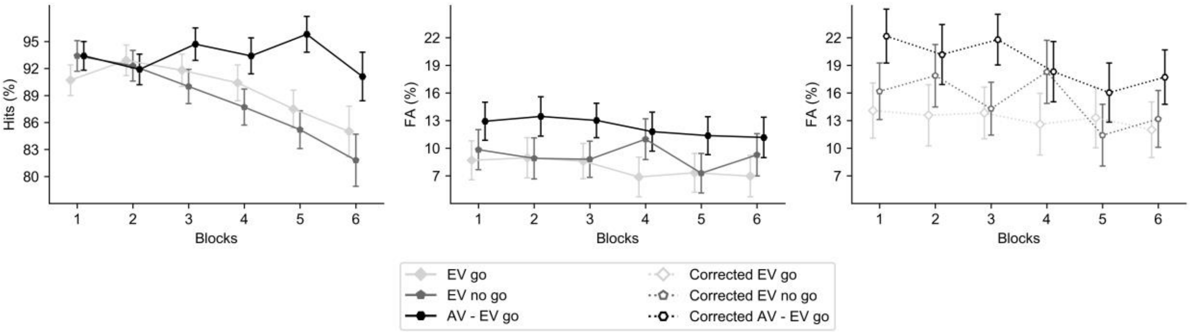

Fig. 6 Hits and false alarms (FA) for the singles and dual vigilance task across time on task. FA rate computed with all trials is shown in the central graph, and the corrected computation on the right graph. Bars represents SE.

Sensitivity

As can be observed in Fig. 7, A’ computed from all trials tended to decrease across blocks [F (5, 330) = 3.60, p = .003, η_p^2 = .05], as a consequence of the decrement on the hits and the non-change in FA rate (computed from all trials). The main effect of task version was far from significance [F (2, 66) = 0.47, p = .629, η_p^2 = .01]. The overall A’ was similar for the EV go (A’ = .95), EV no go (A’ = .94), and AV – EV go task (A’ = .95). In addition, task version showed a small and marginal modulation in the A’ decrement [F (10, 330) = 1.62, p = .099, η_p^2 = .05]. The two single EV tasks revealed a linear decrement more pronounced than the dual vigilance task [F (1, 66) = 4.65, p = .034, η_p^2 = .07], in which A’ tended to increase until the 5th block.

Most importantly, as can be observed in Fig. 7, the corrected computation of A’ did not show any change across blocks [F (5, 330) = 1.68, p = .139, η_p^2 = .02]. In addition, no main effect of task version [F (2, 66) = 0.60, p = .553, η_p^2 = .02], or modulation over blocks was observed [F (10, 330) = 1.39, p = .183, η_p^2 = .04]. The overall corrected computation of A’ was slightly smaller than that obtained from all trials for all task versions (EV go corrected A’ =

.94; EV no go corrected A’ = .92; and AV – EV go corrected A’ = .93). Post-hoc comparisons confirmed the same pattern observed for the total computation of A’. That is, whilst in both single EV tasks the corrected A’ tended to decrease across time, in the dual task it tended to increase (at least until the 5th block) [*F* (1, 66) = 6.03, *p* = .016, η_p^2 = .08], which explain the absence of the main effect of change across blocks.

Response bias

As can be observed in Fig.7, B” computed from all trials showed an increment across blocks [*F* (5, 330) = 4.05, *p* = .001, η_p^2 = .06], together with a main effect of task version [*F* (2, 66) = 3.84, *p* = .026, η_p^2 = .10]. In general, B” was more liberal in the dual task (AV – EV go B” = -.26), than in both single vigilance tasks (EV go B” = .08; EV no go B” = .13). Although task version did not significantly modulate the increment of B” across blocks [*F* (10, 330) = 1.05, *p* = .397, η_p^2 = .03], the two single EV tasks did show a linear increment of B” [*F* (1, 66) = 15.05, *p* < .001, η_p^2 = .19], whereas the dual vigilance task did not have a linear change over time on task (*F* < 1). The comparison between the linear component of the two single EV tasks against the AV - EV go task only approached the significance level [*F* (1, 66) = 2.98, *p* = .088, η_p^2 = .04].

The corrected computation of B”, as can also be observed in Fig.7, did confirm the increment across blocks [*F* (5, 330) = 4.91, *p* < .001, η_p^2 = .07]. Although this increment was again not modulated by task version [*F* (10, 330) = 1.34, *p* = .209, η_p^2 = .04], there was a marginal main effect for task version [*F* (2, 66) = 3.07, *p* = .053, η_p^2 = .09]. In general, the dual vigilance task showed the most liberal B” (AV – EV go corrected B” = -.40), compared to both single vigilance tasks (EV go corrected B” = -.08; EV no go corrected B” = -.06). Again, the two single EV tasks did have a linear increment in the corrected B” [*F* (1, 66) = 14.85, *p* < .001, η_p^2 = .18], but not the dual vigilance task [*F* (1, 66) = 1.07, *p* = .304, η_p^2 = .02]. The linear component of the two single EV tasks was not significantly different from the AV – EV go task [F (1, 66) = 2.06, p = .155, η_p^2 =.03].

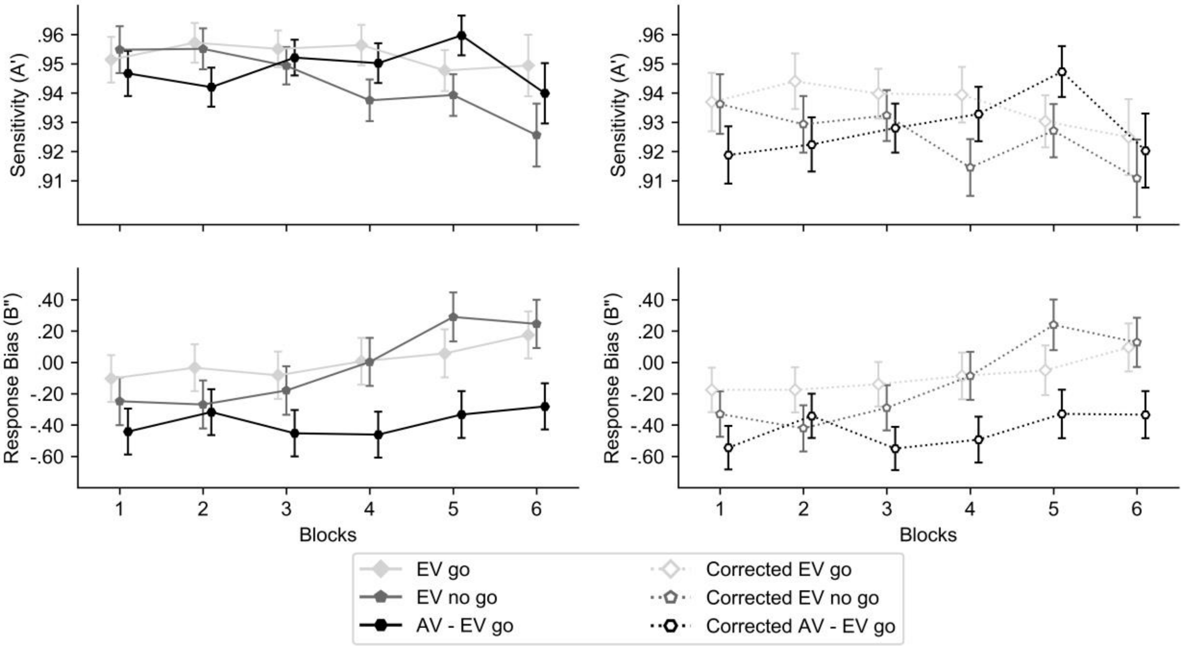

Fig. 7 Sensitivity and response bias across time on task for the singles and dual vigilance task over time on task. In the top graphs, it is shown the computation of sensitivity with all (left) or only corrected (right) trials. In the bottom graphs, it is represented the computation of response bias with all (left) or only corrected (right) trials. Bars represents SE.

Arousal vigilance decrement

Mean RT

As can be observed in Fig. 8, a main effect for task version was observed [F (1, 46) = 13.23, p < .001, η_p^2 = .22], with a higher overall RT for the dual (AV – EV go M = 447 ms) than the AV single task (M = 391 ms). In addition, there was a significant main effect of blocks for mean RT [F (5, 230) = 4.64, p < .001, η_p^2 = .09], and also a modulation of this effect by task version [F (5, 230) = 3.29, p = .006, η_p^2 = .07]. While in the single task there was a clear linear increment in mean RT across blocks [F (1, 46) = 18.25, p < .001, η_p^2 = .28], in the dual vigilance task no linear change was observed [*F* (1, 46) = 0.15, *p* = .703, η_p^2 = .01]. Post-hoc comparisons confirmed that the linear components of these task versions were significantly different from one another [*F* (1, 46) = 7.56, *p* = .008, η_p^2 = .14].

RT Variability

As can be observed in Fig. 8, the SD of RT showed a significant increment across blocks [*F* (5, 230) = 3.79, *p* = .002, η_p^2 = .08], which, in contrast to mean RT, was not modulated by task version [*F* (5, 230) = 0.25, *p* = .940, η_p^2 = .01]. The SD of RT tended to increase similarly, in both the single [*F* (1, 46) = 3.59, *p* = .064, η_p^2 = .07], and the dual task [*F* (1, 46) = 7.56, *p* = .008, η_p^2 = .09]. Post-hoc comparisons confirmed that these linear increments were not different from one another (*F*<1). In addition, it was not observed a main effect of task version [*F* (1, 46) = 0.26, *p* = .616, η_p^2 = .01]. Both the single (AV = 81) and the dual vigilance task (AV – EV go = 85) showed a similar overall SD of RT.

Lapses percentage

As can be observed in Fig.8, as with the SD, and in contrast to the mean RT, lapses also increased across blocks [*F* (5, 230) = 5.11, *p* < .001, η_p^2 = .10], without a modulation by task version [*F* (5, 230) = 0.09, *p* = .994, η_p^2 = .01]. Lapses percentage increased linearly for both the single [*F* (1, 46) = 5.90, *p* = .019, η_p^2 = .11], and the dual task [*F* (1, 46) = 5.29, *p* = .026, η_p^2 = .10]. Post-hoc comparisons confirmed that these linear increments were not different from one another [*F* (1, 46) = 0.04, *p* = .833, η_p^2 = .01]. Moreover, task version effect was far from significance [*F* (1, 46) = 0.01, *p* = .927, η_p^2 = .01]. The overall lapses percentage was similar for the single (AV *M* = 3.82%, *SD* = 5.54) and the dual vigilance task (AV – EV go *M* = 5.43%, *SD* = 7.83).

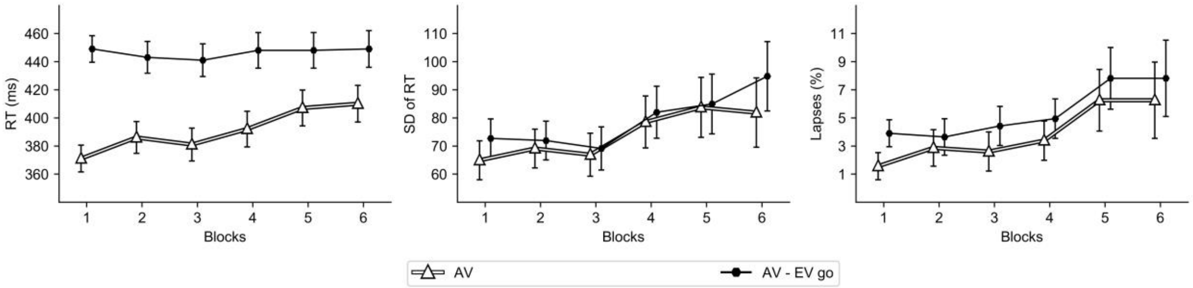

Fig. 8 Arousal vigilance decrement in the single and dual vigilance tasks. Mean RT (left graph), SD of RT (center graph), and Lapses percentage (right graph). Bars represents SE.

Discussion

In this second experiment, we aimed at testing whether the resources overload and the mind wandering accounts are appropriate frameworks to predict the vigilance decrement in two different levels of cognitive load. In line with the resources overload perspective, we would expected a larger decrement in the dual task than in the simple tasks (R. A. Grier et al., 2003). In contrast, according to the mind wandering account, it would be probable that the dual task increases the engagement to solve the activity, reducing the emergency of task-unrelated-thoughts, and thus improving performance (Smallwood & Schooler, 2006). Furthermore, we expected to determine whether the floor effect in the FA biases the EV decrement when it is assessed either through simple and monotonous tasks, or by a more demanding (but less complex than the ANTI-Vea) task, like the dual vigilance task used here.

We observed that, in the EV component, participants performed better the dual task than the two single task. To start with, both the highest overall hits rate and the most liberal response criterion were observed in the dual task. Most important, while in the dual task both the hits rate and the response bias showed no change across time, in both single tasks we observed a linear decrement in the hits, and a linear shifts towards a more conservative response criterion. Besides, whereas there were no overall differences between tasks in the FA rate and the sensitivity, in the dual task there was a progressive increment in sensitivity, in contrast to the decrement revealed in both single tasks. Regarding the AV component, and reflected in the mean RT, while in the dual task we observed a stable performance, in the single task performance tended to a linear increment. These results seems to be inconsistent with previous evidence supporting that an increment on the cognitive loads leads to a larger depletion on the attentional resources, and therefore to a larger vigilance decrement (Epling et al., 2016; Head & Helton, 2014; Helton & Russell, 2011).

Regarding to the role of the FA rate in the EV decrement, we replicated some results previously observed in Experiment 1. Again, in the corrected computation, the FA rate increased importantly with respect to the rate computed including all trials from noise. Interestingly, the shifts in the sensitivity and response bias were clearly modulated by the cognitive load of the task. The sensitivity loss, a widely-reported effect when vigilance is assessed by simple and monotonous tasks (See et al., 1995), was only observed in both single tasks. However, when FA are not at floor, non-parametric indices of SDT are suitable to demonstrate a relevant increment in the response bias, as it was recently reported by Thomson et al. (2016) and Claypoole et al. (2018). Conversely, in the dual task, sensitivity tended to increase (until the 5th block), whilst response bias showed no change across time.

In sum, in this second experiment, wherein we manipulated the cognitive load of the task in order to assess predictions derived from the resource overload and mind wandering accounts, the data seem to challenge the resource overload theory by the observation that an increment in the cognitive load does reduce rather than increase the vigilance decrement. Additionally, and importantly, another main assumption derived from theoretical models of vigilance states that staying vigilant is subjectively experienced as stressful (Thomson, Besner, et al., 2015). In order to specifically test this statement, in the next section we analyzed the self-reported level of mental and physical fatigue across the session, when performing the vigilance tasks in both Experiment 1 and 2. In particular, and according to the resources overload model, the largest mental fatigue should be experienced in the task with the highest cognitive load (i.e., the ANTI-Vea) as compared to the dual or single vigilance tasks (R. A. Grier et al., 2003; Warm et al., 2008). From the mind wandering account, in contrast, the simple EV tasks could be the most under stimulating activities to perform, and therefore it could lead to the greatest experience of mental fatigue, as compared to the dual task or the ANTI-Vea (Smallwood & Schooler, 2006). We also reckon that changes in physical fatigue are more related to the AV component, as this component seems to be associated with shifts in the physiological levels of arousal in long periods (Lim & Dinges, 2008; Sarter et al., 2001).

Mental and physical fatigue as a function of the cognitive load

Table 2 shows the mental and physical state of fatigue at three different times of the session, and for each of the experimental task performed in the current study. The analog assessment of fatigue was transformed into a numeric score, by dividing the line of assessment in nine equal segments. Thus, for example, if a participant clicked in the visual line within the forth segment, the rate of fatigue was transformed to a score equal to four. Note that this allow us to have an auto informed state of both the mental and physical fatigue in a similar scale for all the sample of the current study.

Table 2. Mean and SD (between parentheses) of the mental and physical state of fatigue for each group and period of the session.

	Mental Fatigue			Physical Fatigue		
	Baseline	Pre task	Post task	Baseline	Pre task	Post task
Single Task						
EV go	3.65 (2.06)	4.09 (2.11)	6.69 (1.72)	3.43 (1.93)	4.22 (1.86)	5.56 (2.02)
EV no go	3.77 (1.54)	4.77 (1.57)	6.95 (1.78)	3.91 (1.80)	4.36 (1.73)	5.77 (2.31)
AV	4.12 (1.75)	4.46 (1.79)	6.08 (1.79)	4.12 (1.75)	4.25 (2.09)	5.71 (1.97)
Dual Task						
AV - EV go	3.96 (1.40)	4.67 (1.58)	6.17 (1.78)	3.96 (1.52)	4.37 (1.76)	5.46 (2.10)
Triple Task						
ANTI-Vea - standard	3.45 (1.52)	3.58 (1.72)	5.02 (1.90)	3.42 (1.85)	3.45 (1.81)	4.95 (2.01)
ANTI-Vea - lure	3.46 (1.71)	3.95 (1.82)	5.69 (1.86)	3.61 (1.51)	3.87 (1.57)	5.23 (1.71)

For the following analyses, as there were not relevant differences in the decrement and overall performance between the two groups that performed the single EV tasks, we decided to collapse both groups as a single one (*N* = 45). Moreover, we decided to exclude the data from the lure version, because the single (i.e., EV go and EV no go) and the dual (i.e., AV – EV go) tasks were all based on the procedure of the standard ANTI-Vea task. We take this decision after revisiting that, in Experiment 1, there were no main effects nor modulations of task version (standard/lure) over the mental or physical fatigue state across the session (both *Fs* < 2, *p* > .170).

Then, in order to analyze whether the mental and physical fatigue changed differently across time as a function of cognitive load, we conducted two repeated measures ANOVAs (one for each type of fatigue), including as a within-participant factor the period of the session (baseline/pre task/post task), and cognitive load as a between-participant factor (four groups: EV single, AV single, dual task, triple task). As can be observed in Table 2, as expected, both the mental [F (2, 258) = 110.87, p < .001, η_p^2 = .46] and the physical [F (2, 258) = 96.02, p < .001, η_p^2 = .43] fatigue state showed a relevant increment across session period. Importantly, only the mental fatigue revealed a clear modulation of cognitive load across the session [F (6, 258) = 3.21, p = .005, η_p^2 = .07], whereas this modulation was far from significance for the physical fatigue [F (6, 258) = 1.02, p = .415, η_p^2 = .02].

The post-hoc comparisons demonstrated that groups did not differ at the baseline period, neither in the mental nor in the physical fatigue state (both *Fs* < 1, see Table 2). More importantly, the EV single group showed the largest increment of mental fatigue between the pre and post task periods [F (1, 129) = 87.45, p < .001, η_p^2 = .40], which was significantly different from that observed in the dual task [F (1, 129) = 4.28, p = .041, η_p^2 = .03], and in the triple task group [F (1, 129) = 6.45, p = .012, η_p^2 = .05], and marginal in contrast to the single AV group [F (1, 129) = 3.17, p = .077, η_p^2 = .02]. In contrast, the physical fatigue did not increase differently from the pre to post task period, between the EV single group and the dual or the triple task group (both *Fs* < 1). Finally, the AV single group did not show a larger increment neither in the mental or physical fatigue, in contrast to the dual or triple task group (all *Fs* < 1). Therefore, in summary, the EV single group seems to be the one for which the mental (and not physical) fatigue showed the most prominent increment after performing the task, a piece of data that again seems to challenge the resource overload theory.

General Discussion

The present research addressed several important methodological issues in the study of vigilance, questioning the existing theoretical frameworks about the vigilance decrement phenomenon. The EV decrement has been traditionally assumed as a loss in sensitivity, a behavioral effect that, from the resources overload theory, has been explained by the assumption that staying vigilant is stressful and requires hard mental work, and thus the available attentional resources are depleted across time on task (R. A. Grier et al., 2003; See et al., 1995; Warm et al., 2008). Recently, however, it has been proposed that the loss in sensitivity might be an analytical bias observed in simple vigilance tasks, wherein it is usually found a floor effect in the FA. Indeed, it has been demonstrated that when FA are not at floor, the EV decrement is observed as a shift in the response bias and not as loss in sensitivity, which might be what really underlies the vigilance decrement (Claypoole et al., 2018; Thomson et al., 2016). Thus, the study of vigilance by cognitively simple and repetitive behavioral tasks seems to be a methodological approach that has demonstrated several theoretical and empirical limitations when attempting to account for the vigilance decrement phenomenon (Fortenbaugh et al., 2017; Scerbo, 1998; Thomson, Besner, et al., 2015; Thomson et al., 2016). In order to overcome this critical issue, we decided to assess the vigilance components with the ANTI-Vea, a complex task suitable to measure, simultaneously and within a single session, the EV and AV components together with the classic attentional networks functions (Luna et al., 2018).

In Experiment 1, we addressed the analytical prediction stated by Thomson et al. (2016) about whether a considerable increment in the FA rate can reveal an increase in response bias across time on task rather than a loss in sensitivity (as traditionally assumed). In Experiment 2, we manipulated the cognitive load of the task (i.e., dual vs. single tasks), at difference to the triple task (i.e., ANTI-Vea) used in Experiment 1, in order to assess the predictions derived from the resource overload theory about the scarcity of attentional resources, in contrast to the predictions derived from mind wandering theory regarding the attentional engagement to perform the activity at hand. Finally, by analyzing the self-reported level of mental and physical fatigue in both experiments, we tested whether the conception that vigilance tasks are subjectively experienced as stressful would be due to the hard cognitive effort demanded by the task (as predicted by the resources overload theory), or to the monotonous and boring character of the activity (as explained by the mind wandering account). The main results will be discussed separately in the following sections.

Signal-Noise Similarity Modulates the Executive Vigilance Decrement

With respect to the EV component – which has been traditionally measured by signal detection tasks – there has been a long-standing discussion about whether the decrement corresponds to a loss in the sensitivity or to an increment in the response bias (See et al., 1995, 1997; Thomson et al., 2016). In order to address this issue, Thomson et al. (2016) recently proposed a novel analytical method with the aim to elucidate whether a low rate in the FA could be masking a potential shift in the response bias. In particular, to observe an increment in the response bias, the decrement in the hits should be accompanied by a similar drop in the FA, which is very unlikely if the FA are already at floor at the beginning of the task. Moreover, Thomson et al. strongly objected the application of parametric indices of SDT when FA are 0%, a rate that is probably observed when data are analyzed by blocks, and also when participants perform very easy demanding tasks, such as the traditional simple vigilance tasks (Conners, 2000; Mackworth, 1948; Robertson et al., 1997).

Based on these previous concerns, we computed here a corrected FA rate, considering only the noise trials most similar (i.e., the lures) to the signal ones. As expected, and in line with the previous findings of Thomson et al. (2016), we clearly observed in both Experiment 1 and 2 that the corrected FA rate was effectively quite higher than the traditional computation including all the noise trials. Importantly, the FA rate did not increase across time in none of the vigilance tasks, something that could raise the probabilities to observe a decrement in sensitivity. Note that, however, in the ANTI-Vea task, the corrected computation confirmed that sensitivity did not decrease across time, an effect that was found with sensitivity being computed considering all noise trials.

Notwithstanding, we consider that in the opened-debate about whether the shifts across time on task occurs in the response bias or the sensitivity, we must necessarily consider the methodological approach used to assess vigilance, and in particular, the signal-noise similarity together with the cognitive load of the task (Thomson, Besner, et al., 2015). There is a long tradition in studying vigilance as the sustaining of attention in long, repetitive, and intellectually unchallenging tasks (Langner & Eickhoff, 2013; Warm et al., 2008). Nevertheless, whilst several researches support that an increment on task-demands leads to a larger decrement (Epling et al., 2016; Head & Helton, 2014; Helton & Russell, 2011), others studies report an absence of decrement when the administered task is more difficult and complex (Moray & Haudegond, 1998; Thomson, Smilek, & Besner, 2015) or when there is a greater task-engagement (Pop, Stearman, Kazi, & Durso, 2012). Thus, in order to disentangle whether an increment in the cognitive load of the task leads to a larger decrement, as predicted by the resources overload theory (Warm et al., 2008), or to a more stable performance across time, as anticipated by the mind wandering account (Smallwood & Schooler, 2006), in the following section we discuss the current findings regarding the EV and AV decrement in three different levels of cognitive load.

The Cognitive Load Modulates Differently the Executive and Arousal Vigilance Decrement

Interestingly, we have observed that sensitivity and response bias reflect different shifts across time as a function of the cognitive load of the task. For instance, the sensitivity loss – a widely-reported effect in the vigilance decrement (See et al., 1995) – was only observed with the simple tasks used in Experiment 2, which were similar to the traditional vigilance tasks as the MCT or the SART. Importantly, and confirmed by the methodological approach proposed by Thomson et al. (2016), we observed a relevant increment in the response bias only with the simple tasks, and with most complex and demanding task (i.e., the ANTI-Vea). Instead, with the dual-task of Experiment 2, there was no shift in the response bias and, indeed, sensitivity tended to increase at least until the 5th experimental block.

It is worth mentioning that, regarding the AV component, we observed that with the simple task (i.e., similar to the PVT), the increment in the mean RT was larger than with the ANTI-Vea task, whilst with the dual task there was no shift at all. However, note that if the decrement is analyzed in the RT variability, then it can be observed that the progressive increment of variability is completely independent of the cognitive load of the task ($F < 1$, even when the three task loads are considered). The shift in RT variability has been considered as evidence of two different vigilance states: ‘in the zone’, in which there is a more stable performance and less probability of errors, or ‘out of the zone’, wherein there is less stability and therefore, it is more likely that attentional lapses occurs (Esterman et al., 2013). From this perspective, it could be possible that the AV component would be more independent from the cognitive loads of the task than the EV component. Further studies are, however, required to better clarify this issue.

Taken the two experiments together, it seems clear that the highest level of performance relies in an optimal level of workload (that is not the lowest nor the highest), as it would be anticipated by the inverted-U function hypothesis (Wiener, Curry, & Faustina, 1984). However, this optimal level in a dual task might rather depend on the nature of the task demands and/or the cognitive processes involved in its resolution, than in just the quantity of tasks to perform simultaneously. For instance, in Luna et al. (2018; Experiment 1), by using a different dual task (i.e., the ANTI-V), wherein participants were asked to perform a signal detection task and a flanker paradigm simultaneously, it was found a relevant increment in the response bias.

Note that also, importantly, whilst in the current dual task participants reached an overall ~93% of hits, in that ANTI-V participants reached quite lower rate, i.e., ~62% (Luna et al., 2018). Thus, it seems imperative to review whether the most widely accepted theoretical frameworks concerning the vigilance decrement are adequate to anticipate modulations of this phenomenon within a varied set of task-demands, when controlling for other task and stimuli conditions, as we did in the present study.

Are the Existing Theoretical Models Adequate Frameworks to Explain the Vigilance Decrement?

The resources overload view is still the leading account regarding the vigilance decrement, and it is mainly based on the assumptions that staying vigilant requires hard mental work and is subjectively experienced as stressful (R. A. Grier et al., 2003; Warm et al., 2008). From this perspective, there would be a larger decrement across time in tasks with concurrent cognitive load, as a consequence of a faster depletion of the available attentional resources (Head & Helton, 2014). In contrast, the mind wandering account predicts that resources are re-directed – rather than depleted – to internal irrelevant thoughts, unnecessary to perform the task at hand (Smallwood & Schooler, 2006). Following this latter account, simple and repetitive vigilance tasks results quite boring to participants, and thus vigilance decrement is reduced when the task increases the engagement to solve the activity (Danckert & Merrifield, 2016; Thomson, Besner, et al., 2015). Indeed, and in the same vein, a recent empirical and meta-analytical study has demonstrated that, under the same conditions, the mere perception of multi-tasking enhances task engagement and improves performance in contrast to the perception of performing a single task (Srna et al., 2018).

In particular, the resources overload model cannot appropriately explain why participants could perform better the current dual task than any of the simple ones. In addition to this, and importantly, participants experienced the greatest mental workload with the simple tasks than with the dual or triple ones. Therefore, we reasoned that if the complexity of the task does increases the engagement to solve the activity (reducing the emergency of task-unrelated-thoughts), it makes sense that the dual task improves performance in comparison to the simple tasks. However, this reasoning presents limitations in explaining the larger decrement observed in the triple than in the dual task. Note that, when analyzing the hits rate across blocks as a function of the cognitive load of the task (i.e., including three levels: the simple task – as a group with both single EV tasks –, the dual task, and the triple task – i.e., the standard version of the ANTI-Vea), there is no shift at all in the dual task ($F < 1$), and indeed, the linear decrement is more prominent in the simple tasks in contrast to the dual task [F (1, 106) = 6.37, p = .013, η_p^2 = .06], and also in the triple task compared to the dual one [F (1, 106) = 5.19, p = .025, η_p^2 = .05].

Thus, additional accounts beyond the ones presented above should be considered to better understand these outcomes. In this line, the resources-control model has been recently proposed as an alternative explanation to the vigilance decrement (Thomson, Besner, et al., 2015). This model is based on the assumption that there is a permanent amount of attentional resources, which initially are at equilibrium between the task being performed and mind wandering (the by default mind state), for which executive control is necessary. However, across time on task, there would be a relevant drop in executive control, which is necessary to prevent the emergency of task-unrelated-thoughts, and to maintain the attentional focus on the external activity (Thomson, Besner, et al., 2015). We consider that this alternative framework fit well with the findings observed here with the simple tasks, wherein the low level of cognitive load, and the monotonous and boring character of the activity, leads to an important loss in performance and also to the greatest experience of mental fatigue. When the cognitive load of the task is increased (as in the current dual task condition), it would be possible to maintain cognitive control on the external activities, thus considerably reducing the levels of mind-wandering, and sustaining an optimal performance. Importantly, the fact that dual task conditions indirectly maintain attentional resources on the task would make easier to prevent mind-wandering, which can explain the reduced levels of self-reported cognitive fatigue observed in the dual compared to the single task condition.

It should be noted that, in line with the linear decrement observed in the EV performance with the simple and triple tasks, the mental fatigue showed the most prominent increment in the simple tasks, but also a considerable raise in the triple task (see Table 2). Nonetheless, neither the resources overload nor the mind wandering account seems appropriate to completely clarify the levels of mental fatigue experienced after performing either a simple or a quite complex task (i.e., the triple task). Although the mind wandering account could explain the mental fatigue reported with the simple tasks as a result of the monotonous and boring character of the activity (Danckert & Merrifield, 2016; Thomson, Besner, et al., 2015), with participants feeling quite tired and stressed after staying approximately half an hour performing a vigilance task quite simple and repetitive, this account cannot successfully elucidate the mental fatigue reported in the triple task. In this case, on the contrary, the mental fatigue might be understood as a consequence of the high demands imposed by the task, which requires several and different cognitive process necessary to perform the multiple tasks at hand.

Following the resources-control perspective, it could be possible that in a complex and high-demanding task such as the ANTI-Vea, the attentional resources would be mainly distributed between the principal and secondary activities, rather than between the single external task and the emergency of internal irrelevant thoughts, as it seems to occur in a simple task. Thus, in a complex task, the performance costs could be reflected as a small decrement in all the several tasks demanded, whilst in a simple task the emergency of internal irrelevant thoughts would demand a great amount of the attentional resources, causing a great impact on the decrement of performance. Interestingly, this logic is also in line with data from our previously mentioned large data sample collected by the standard and online version of the ANTI-Vea, wherein we observed a small but relevant reduction on the cognitive control functioning in the RT [F (5, 2945) = 10.13, p < .001, η_p^2 = .02], measured as the increment of the interference effect across blocks, which was not modulated by the version of the task (F < 1; Luna et al., 2019). Thus, although this progressive loss of cognitive control can be considered as a critical evidence supporting the resources-control model proposed by Thomson, Besner, et al. (2015), further studies are required to better develop appropriate theoretical accounts that might explain the vigilance decrement phenomenon in relation to a wide set of cognitive loads.

Conclusions

The present research aimed at testing several theoretical and methodological issues derived from simple and monotonous tasks traditionally used to study the vigilance decrement phenomenon. These methodological approaches have supported the development of theoretical frameworks such as the resources overload and mind wandering accounts, which seems to be inadequate to predict the vigilance decrement within a complex set of cognitive loads. By using the ANTI-Vea task here, we aimed at dissociating several attentional components across different levels of cognitive demands, providing further evidence that the ANTI-Vea is a suitable method to assess the EV and AV components, together with the classic attentional networks functions (Luna et al., 2018).

In two experiments, we analyzed the decrement in the EV and AV components across three different levels of cognitive loads. Regarding the EV component, the sensitivity loss was found only with the simple tasks (See et al., 1995), wherein participants also reported the greatest subjective mental fatigue. In addition, when FA were not at floor, we observed a relevant increment in the response bias (Claypoole et al., 2018; Thomson et al., 2016), an effect found with both the simple and the triple task. With respect to the AV component, the increment in RT variability across time on task was completely independent from the cognitive load of the task, in contrast to mean RT in AV and other indices of EV, which were highly dependent on the task load. Interestingly, the dual vigilance task administered here can be interpreted as an optimal level of workload, wherein there was no decrement at any in the EV metrics, and the mean RT in the AV component was stable across time.

In conclusion, the current study provides strong and novel evidence that challenges the classical theories when attempting to account the vigilance decrement phenomenon in a wide range of cognitive demands. The present findings raise the need either to re-conceptualize the existing frameworks, or to develop novel approaches, with the imperatively requisite to overcome the theoretical and methodological limitations previously presented at explaining the potential shifts in performance over long time periods (i.e., in the vigilance decrement), and to keep attempting to dissociate both theoretically and empirically the two vigilance components as we offered here. Thus, these findings have critical implications for both better understanding the empirical modulations on the EV and AV components as a function of the task demands, and to the theoretical accounts regarding the vigilance decrement phenomenon.

Chapter V

Experimental Series 3

The split-half reliability of the standard and the online ANTI-Vea

The content of this chapter is in preparation:

Luna, F.G., Roca, J., Martín-Arévalo, E., and Lupiáñez, J. The split-half reliability of the standard and the online ANTI-Vea.

Abstract

Over the last years there has been a growing interest in using online methods for collecting large sample sizes. However, only a few studies have administered online behavioral tasks to assess vigilance outside the lab to date. In the present study, we assessed the classic attentional functions and vigilance components by using two versions of the Attentional Networks Test for Interactions and Vigilance – executive and arousal vigilance components (ANTI-Vea): (a) a standard version, performed under typical experimental conditions (*n* = 314), and (b) an online version, completed outside the lab (*n* = 303). Both versions were equally effective to assess: (a) the main effects and interactions of phasic alertness, orienting, and executive control; and (b) the executive (i.e., a decline in the ability to detect infrequent critical signals) and the arousal (i.e., a progressive slowness in responses to stimuli from environment) vigilance decrement across time on task. Responses were in general slower in the online version as compared to the standard one. Furthermore, the split-half reliability observed for both tasks was: (a) higher for executive control (~.67) than for phasic alertness and orienting (< .40); and (b) moderate to high (between .71 and .99) for the executive and arousal vigilance measures. We expect the present study would be of interest for researchers aiming to assess attentional and vigilance components with a reliable method that, importantly, is publicly available in an open website (https://www.ugr.es/~neurocog/Sitio_web/ANTI/), and easy to use in applied contexts.

Introduction

According to a widespread theory on attention, attentional processes are supported by three independent networks which, nevertheless, may interact with each other (S. E. Petersen & Posner, 2012; Posner & Petersen, 1990). In particular, (a) the alerting network underlies both phasic alertness (i.e., a brief increment of arousal) and vigilance (i.e., sustaining attention over extended periods of time) (Posner, 2008); (b) the posterior network directs attentional orienting towards a potential relevant source from the environment for stimuli selection (Posner, 2014); and (c) the anterior network modulates executive control processes to adapt our behavior for long term goals (Shenhav et al., 2013). With the aim to simultaneously assess the different components of the attentional networks, there is a considerable interest in developing extended and more sensitive versions of the classical Attentional Networks Test (ANT) (see e.g., Callejas, Lupiáñez, & Tudela, 2004; Fan, McCandliss, Sommer, Raz, & Posner, 2002; Roca, Castro, López-Ramón, & Lupiáñez, 2011). In the present study, we examined the feasibility of a new version of the ANT (i.e., the ANTI-Vea; Luna, Marino, Roca, & Lupiáñez, 2018) developed to assess, both in the lab and through an online website, the classic attentional functions (i.e., phasic alertness, orienting, and executive control) along with two different components of vigilance: executive vigilance (EV) and arousal vigilance (AV). In addition, to further examine whether attentional tasks can be easily and reliably administered online (Claypoole et al., 2018), we provide new evidence concerning the reliability of the ANTI-Vea measures obtained both in the typical lab conditions and by online assessment.

The Attentional Networks Test and its Reliability

To assess the independence and efficiency of the three attentional networks in a single session, Fan et al. (2002) developed the ANT, a behavioral task that combines a spatial cueing paradigm (Posner, 1980) and a flanker task (Eriksen & Eriksen, 1974). Later on, Callejas et al.

(2004) proposed a modified version of the ANT (i.e., the ANT for Interactions, or ANTI) with the aim to further assess both the independence and the interactions between the attentional networks components. In the ANTI, to assess the executive control network, participants have to perform a flanker task by responding only to the direction pointed by the target (i.e., a central arrow) while ignoring the direction pointed by the surrounding flanking arrows. To respectively assess the phasic alertness and the orienting networks, prior to the appearance of the target and flankers above or below the fixation point, the string of arrows can be (a) anticipated or not by an auditory warning tone, and (b) predicted by either a valid spatial cue (i.e., an asterisk appearing at the same location), an invalid spatial cue (i.e., an asterisk appearing at the opposite location), or by no cue.

Importantly, although the ANT and the ANTI are appropriate to assess the classic attentional components, these tasks can only provide indirect measures of vigilance, such as the overall reaction time (RT) or the RT difference between the last and the first experimental block (Callejas et al., 2005; Ishigami & Klein, 2010). To overcome this limitation, Roca et al. (2011) developed the ANT for Interactions and Vigilance (ANTI-V), which indeed assess vigilance with a task similar to the classical Sustained Attention to Response Task (SART; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997) or the Continuous Performance Test (CPT; Conners, 2000). Thus, in the ANTI-V, participants perform the ANTI task in most trials (75%) but they have to maintain vigilant to detect an infrequent (25% of trials) displacement of the target from its central position.

Interestingly, in previous studies wherein the psychometric properties of the ANT and the ANTI were analyzed, only executive control has shown a moderate to high reliability, whereas phasic alertness and orienting usually show a low to moderate reliability (J Fan et al., 2002, 2001; Ishigami & Klein, 2010; MacLeod et al., 2010). In particular, Ishigami & Klein (2010) reported higher reliability scores for the ANTI than for the ANT, especially for phasic alertness and orienting. The fact that cognitive control shows a much more reliable measure than alertness and orienting might indicate that this represents perhaps an attentional trait, whereas alertness and orienting might rather be related to attentional states (MacLeod et al., 2010). Most importantly, and relevant for the present study, when the reliability of the ANTI-V was examined by using a large sample size ($N = 234$) , the results from the Spearman-Brown prophecy formula applied to the split-half correlations demonstrated that: (a) only executive control showed a moderate reliability (.66), while a low reliability (i.e., below .35) was observed for both phasic alertness and orienting, in the same vein as in previous literature with the ANT and the ANTI (Ishigami & Klein, 2010; MacLeod et al., 2010); and (b) critically, all the vigilance indices showed a moderate to high reliability (i.e., between .71 to .93) (Roca et al., 2018).

Measuring Vigilance Online

In the last years, there has been a notably increment in administering online and self-report methods to collect large sample sizes, a trend that has been partially driven by the imperative need to rise the replicability of results reported in psychological science (Munafò et al., 2017; Sassenberg & Ditrich, 2019). In particular, the online assessment has become a suitable and low cost alternative for researchers interested in achieving a high number of observations within a short period of time. Thus, just to give an example, the last major version of PsychoPy (Peirce et al., 2019) – the Python toolbox for developing psychological experiments – was released along with the Pavlovia project (https://pavlovia.org/), an open access website useful for researchers interested in running, sharing, and exploring online experiments.

Nevertheless, it is worth noting that, in an online session, the experimental conditions would not be as controlled as in the lab, and this concern might be one of the main reasons for which only a few studies have administered vigilance tasks online so far (Fortenbaugh et al., 2017; Ralph et al., 2015; Sadeh et al., 2011; Thomson et al., 2016). Notwithstanding, and importantly, vigilance was successfully measured in the above-cited studies. For instance, whereas Ralph et al. (2015) and Thomson et al. (2016) observed the vigilance decrement phenomenon (i.e., a progressive decline of sustained attention across time on task) through an online signal detection task, Sadeh et al. (2011) found that an online version of the CPT was sensitive to assess the effects of sleep loss deprivation over vigilance performance. Furthermore, the results reported by Thomson et al. (2016) were replicated when the same vigilance task was administered in the typical lab conditions (Claypoole et al., 2018).

The Present Study

Recently, we have developed the ANT for Interactions and Vigilance – executive and arousal components (ANTI-Vea), a new version of the ANT suitable to assess the classic attentional functions (as in the ANTI) along with two different components of vigilance (Luna et al., 2018). In particular, the EV component is measured as the ability to sustain attention over long time periods to detect infrequent critical signals, in line with the CPT (Conners, 2000) or the SART (Robertson et al., 1997). Note that, while the ANTI-V was not suitable to observe the decrement of performance across time on task (Roca et al., 2011), with the ANTI-Vea the EV decrement was found as a progressive increment in the response bias towards a more conservative criterion (Luna et al., 2018), in the same vein as in recent vigilance studies (Claypoole et al., 2018; Thomson et al., 2016). In contrast, the AV component is assessed as in the Psychomotor Vigilance Test (PVT), as the capacity to maintain a fast and automatic reaction to stimuli from the environment without much control (Lim & Dinges, 2008). Importantly, the ANTI-Vea is sensitive to observe the AV decrement as a progressive increment in the mean and variability of RT across time on task (Luna et al., 2018), in line with previous findings reported with the PVT (Basner & Dinges, 2011; Lamond et al., 2008).

Taking the above-mentioned issues into account, we conducted the present study with a two-fold goal: (a) to examine whether the online version of the ANTI-Vea was also suitable to assess the independence and interactions of the classic attentional components along with the EV and AV decrement, as observed in the typical lab conditions; and (b) to further assess the psychometric properties of both task versions, by analyzing the split-half reliability of the attentional and vigilance measures computed in both the standard ANTI-Vea (i.e., administered in the lab) and the online ANTI-Vea. To do so, we designed a publicly accessible website to run and collect online data with the ANTI-Vea (https://www.ugr.es/~neurocog/Sitio_web/ANTI/). Thus, the present study seeks to provide novel evidence for researchers interested in administering an online available and easy to use task to assess the classic attentional functions and the vigilance components within a single session.

Method

Participants

Computing split-half reliability indices generally requires a relative large sample size. Thus, we collected data from 617 participants (see descriptive statistics in Table 1), with either the standard version (*n* = 314) or the online version (*n* = 303) of the ANTI-Vea task. Participants were at least undergraduate students, and most were compensated with extra course credits (0.1/hour). To analyze the performance in the standard ANTI-Vea, we combined data from healthy participants who were included in previous non-clinical studies with the ANTI-Vea (Luna, Barttfeld, Martín-Arévalo, & Lupiáñez, 2019; Luna et al., 2018; Luna, Martín-Arévalo, Foa Torres, & Lupiáñez, 2019; Pirruccio, 2018; Puente-Ontanilla, 2018). Then, we collected data from a similar group size with the online ANTI-Vea. The study was conducted according to the ethical standards of the 1964 Declaration of Helsinki (last update

Seoul, 2008), and was part of a larger research project, which has been positively evaluated by the University of Granada Ethical Committee (536/CEIH/2018).

Table 1. Descriptive statistics of participants that performed the standard or the online version of the ANTI-Vea task. For mean age, the standard deviation is represented between parentheses.

	n	Sex		Age	Location
		Women	Men		
Standard					
Experiment 1[a]	40	20	20	25.48 (6.60)	Córdoba (Argentina)
Experiment 2[b]	42	30	12	22.50 (5.18)	Córdoba (Argentina)
Experiment 3[c]	80	70	10	19.11 (2.16)	Granada (Spain)
Experiment 4[d]	41	34	7	20.10 (3.17)	Granada (Spain)
Experiment 5[e]	49	18	31	31.06 (4.07)	Madrid (Spain)
Experiment 6[f]	62	35	27	25.44 (4.87)	Córdoba (Argentina)
Overall	314	207	107	23.62 (5.94)	
Online					
Subgroup A	150	111	39	23.27 (4.53)	Córdoba (Argentina)
Subgroup B	84	73	11	19.71 (3.53)	Granada (Spain)
Subgroup C	40	33	7	20.60 (2.28)	Valencia (Spain)
Subgroup D	16	12	4	22.63 (1.15)	Padova (Italy)
Subgroup E	13	9	4	23.46 (5.19)	Not informed
Overall	303	238	65	21.91 (4.24)	

Note. [a] Experiment 1 of Luna et al. (2018), [b] Experiment 1 of Luna, Barttfeld, et al. (2019), [c] Experiment 3 of Pirruccio (2018), [d] Experiment 4 of Pirruccio (2018), [e] Puente-Ontanilla (2018), [f] Luna, Martín-Arévalo, et al. (2019).

Apparatus and Stimuli

Following Luna et al. (2018), the standard ANTI-Vea was designed and run in E-Prime v2.0 Professional (Psychology Software Tools, Pittsburgh, PA). In addition, we used JavaScript ES5, HTML5, CSS3, and Angular JS to design and run the online ANTI-Vea. Stimuli and instructions were the same for both versions, and were presented over a grey background and within a screen resolution of 1024 pixels (px) wide × 768 px high. The stimuli set comprised: a black cross (~7 px) as the fixation point, a black asterisk (~13 px) as the visual cue, a tone (2000 Hz) as the warning signal, five black arrows in a row pointing either leftward or rightward (50 px wide × 23 px high each arrow, separated by ~63 px) as the target and flankers, and a red millisecond down counter (~110 px height each number) as the AV stimuli. Responses were collected on a standard keyboard.

Procedure and Design

Participants who performed the standard ANTI-Vea completed the session under typical lab conditions. They performed the task individually in an experimental room, using headphones to hear the warning signal. In contrast, the participants that performed the online ANTI-Vea completed the task at home or in a suitable place of their choosing where they could access the website on a computer. We included additional instructions with the aim of reducing any possible distractions while performing the task online. These additional instructions were presented before the standard instructions, and warned the participants that the task would be displayed full screen, and that it was important to perform uninterruptedly the task until it finished, trying to avoid any distraction as much as possible. In addition, they were asked to set the sound level of the computer at 75%, to turn their mobile phone on mute mode and to turn off the vibration function, trying to keep it out from their reach while performing the task. Moreover, they were asked to turn off any entertainment device (e.g., television or radio). Lastly, if it was necessary to stand up from their seat due to any particular reason, they were suggested to do it before starting the task.

Then, to familiarize participants with the three types of trials of the ANTI-Vea (i.e., ANTI, EV, and AV trials), both groups received specific instructions and completed several practice blocks with visual feedback, as in Luna et al. (2018). The ANTI trials followed the procedure of the ANTI task (Callejas et al., 2004). Participants had to perform a flanker task, responding to the direction pointed by a central arrow (i.e., the target) while ignoring the direction pointed by two distracting arrows at each side. Stimuli could appear randomly above or below the fixation point. To assess the executive control network, in half of these trials the target and the distractors pointed to the same direction (congruent condition), whereas in the other half the distractors pointed to the opposite direction of the target (incongruent condition). In addition, to assess phasic alertness, in half of these trials a warning signal could anticipate the response stimuli (tone condition), whereas in the other half there was no warning signal (no tone condition). Lastly, to assess the orienting network, a visual cue could be presented above/below the fixation point either (a) at the same location as the string of arrows (valid condition, 1/3 of trials), (b) at the opposite location (invalid condition, 1/3 of trials), or (c) not be presented at all (no cue condition, 1/3 of trials). The stimuli sequence and timing, correct responses, and examples of congruency and visual cue for the ANTI trials are depicted in Fig. 1.

The EV trials followed the same procedure of the ANTI ones, with the single difference that the target appeared quite displaced (8 px) from the central position, either upwards or downwards (see Fig. 1). To correctly perform the EV trials, participants were instructed to remain vigilant all time attempting to detect the displaced targets. Importantly, with the aim to make more difficult the detection of the displaced targets, arrows were not presented at exact positions; instead, the vertical and horizontal position of each arrow had a random variability of ±2 px, both in the ANTI (for target and flankers) and EV (only for flankers) trials. Therefore, in the ANTI trials, the maximum vertical distance between the target and one of the two adjacent flankers could be of 4 px, and the minimum of 0 px, whereas in the EV trials it could be between 10 px and 6 px, respectively. Lastly, in the AV trials, neither warning signal nor visual cue was presented before the response stimuli, and participants were instructed to stay vigilant to stop a red millisecond down counter as fast as possible (see Fig. 1).

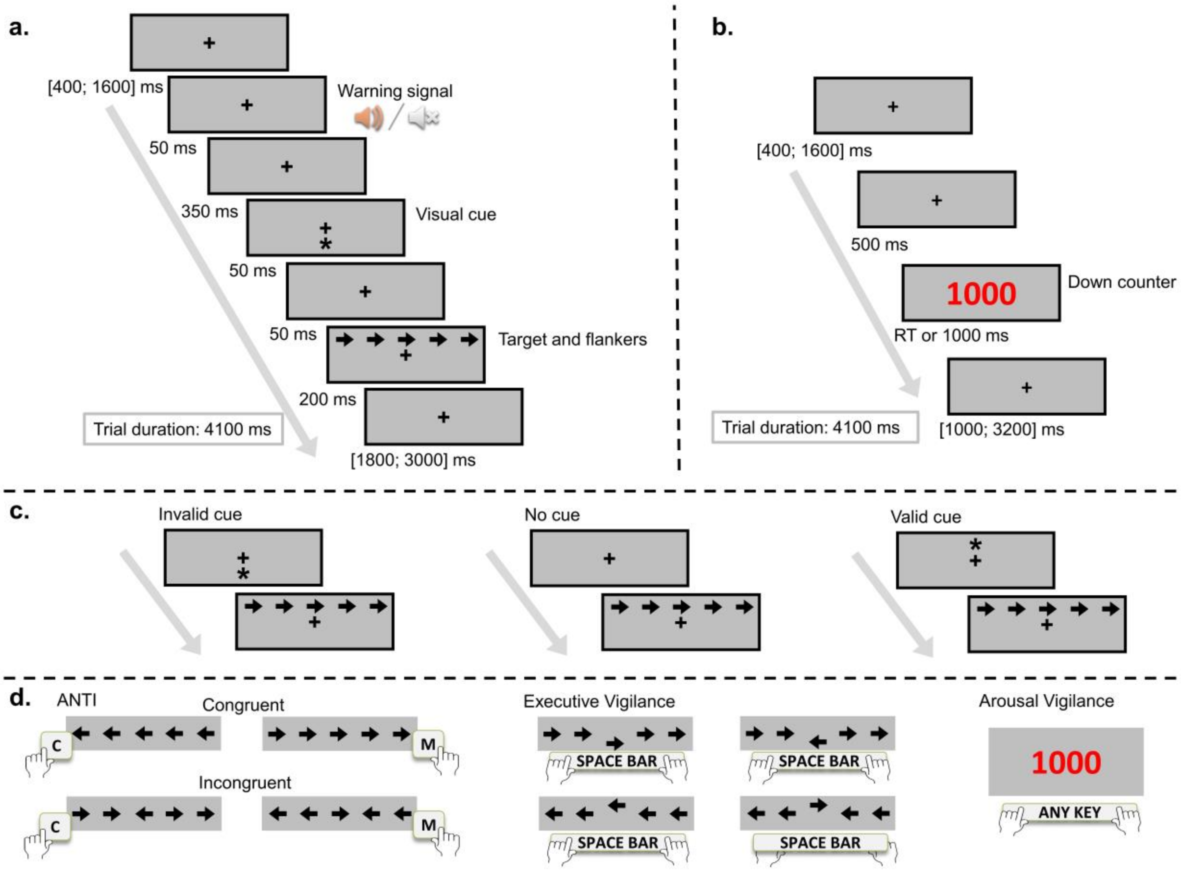

Fig. 1. Procedure of the ANTI-Vea task. (a) Stimuli sequence and timing for the ANTI and EV trials. The first and the last screen had a random timing to set the total trial duration in 4100 ms. Responses were allowed until 2000 ms from the target and flankers appearance. (b) Stimuli sequence and timing for the AV trials. Again, the first and the last screen had a random timing and all AV trials lasted in total 4100 ms. Responses were allowed until 2000 ms from the down counter appearance. (c) Examples of visual cue conditions. (d) The correct responses expected for the ANTI (see examples of congruency condition), EV and AV trials.

Participants completed six experimental blocks, with no pause nor visual feedback, with 80 randomized trials per block (48 ANTI, 16 EV, and 16 AV). The ANTI trials had the following factorial design: Warning signal (no tone/tone) × Visual cue (invalid/no cue/valid) × Congruency (congruent/incongruent). The 16 EV trials per block were randomly selected from all the possible combinations of the ANTI trials.

Statistical Analyses

Twenty-six participants (4.21%) were excluded from further analyses: ten from the standard group and fourteen from the online one due to extreme overall RT or percentage of errors in the ANTI trials (2.5 *SD* above the group mean), and two participants from the standard group due to a technical issue during data acquisition. Then, we conducted separately the analysis of the attentional networks components, the vigilance components, the correlational analyses between the attentional and vigilance components, and the split-half reliability analysis. The analyses of the attentional networks, the vigilance components and correlational analyses were conducted in Statistica 8.0 (StatSoft, 2007). Split-half reliability indices were computed using the plyr (Wickham, 2011) and Hmisc (Harrell, 2018) libraries in R Studio (R Core Team, 2018). Figures were made with Matplotlib 3.0.0 (Hunter, 2007).

Attentional networks components

For the ANTI trials, RT analyses excluded trials with incorrect responses (standard = 6.22%; online = 5.91%), and with a RT below 200 ms or above 1500 ms (standard = 0.51%; online = 0.53%). Then, the analysis of the main effects and interactions of attentional components included two mixed ANOVAs, one for RT data and another for the percentage of errors, with warning signal (no tone/tone), visual cue (invalid/no cue/valid), and congruency (congruent/incongruent) as within-participant factors, and task version (standard/online) as a between-participants factor.

Vigilance components

To analyze the EV and AV decrement across time on task, vigilance measures were computed per block of trials. For the EV trials, warning tone, visual cue, and congruency levels were not considered for analyses, with data being collapsed across these variables. We computed hits (i.e., correct responses in the EV trials) and false alarms (FA; i.e., space bar responses in the ANTI trials) rate. Importantly, with the aim to avoid that a floor effect in the FA could mask a considerable shift in the response bias (Thomson et al., 2016), and following Luna, Barttfeld, et al. (2019), we categorized off-line the ANTI trials as a function of the vertical distance between the position of the target and the closest adjacent flanker, to select only those trials wherein there was a higher chance to commit a FA (Luna, Barttfeld, et al., 2019). Therefore, the FA rate was computed only considering the trials in which this distance was between 3 and 4 px, and the trials wherein this distance was between 0 and 2 px were excluded from EV analyses.

Next, non-parametric indexes of sensitivity (A′) and response bias (B″) were obtained (J. B. Grier, 1971). The advantages of using non-parametric over classic parametric indexes (d′ for sensitivity and β for response bias) to analyze the EV decrement in the ANTI-Vea task are discussed in Luna et al. (2018), and can be reviewed in detail in several studies (Stanislaw & Todorov, 1999; Thomson et al., 2016). Additionally, we obtained the mean and SD of RT on hits per block, excluding trials with a RT below 200 ms and above 1500 ms (standard = 0.77%; online = 0.71%). Then, six mixed ANOVAs were conducted separately, one for each dependent variable (hits, FA, A′ and B″, mean RT, and SD of RT), including block (6 levels) as within-participant factors, and task version (standard/online) as a between-participants factor.

For the AV trials, we computed the mean RT, SD of RT, and the percentage of lapses (i.e., responses slower than 600 ms), following the criterion established in Luna et al. (2018). Then, three mixed ANOVAs were conducted separately, one for each dependent variable (mean RT, SD of RT, and percentage of lapses), including block (6 levels) as a within-participant factor, and task version (standard/online) as a between-participants factor.

Correlations between attentional and vigilance components

The analysis of Pearson’s bivariate correlations included the overall RT and the percentage of errors in ANTI trials, and the overall of the EV and AV measures described above. In addition, we computed the attentional networks scores proposed by Callejas et al. (2004), by subtracting average data in specific conditions: (a) the phasic alertness score as the result of no tone minus tone conditions, only considering trials with no visual cue, (b) the orienting score as the result of invalid minus valid conditions, and (c) the executive control score as the result of incongruent minus congruent conditions.

Split-half reliability

Following the analyses conducted by Roca et al. (2018) with the ANTI-V task, first, all the experimental trials of each participant were split randomly in two halves, as a function of: (a) the ANTI trial condition (i.e., warning signal, visual cue, or congruency) to compute the attentional networks scores, and (b) the type of trial (ANTI, EV, and AV) to compute ANTI overall RT and percentage of errors, and the EV and AV measures. This procedure was repeated by a permutation approach until we obtained 10.000 pairs of trials’ halves. Then, for each permutation, we computed the different attentional network or vigilance measures in each of the two halves. After that, correlations across participants were performed between the two halves. The split-half reliability indices were obtained as the average of the 10.000 correlations for each attentional network or vigilance measure. Finally, we applied the Spearman-Brown prophesy formula to extrapolate the test-retest reliability from the split-half reliability (MacLeod et al., 2010)

Results

Phasic Alertness, Orienting, and Executive Control

The typical main effects of the classic attentional functions, usually reported with the ANTI (Callejas et al., 2004) and the ANTI-Vea (Luna et al., 2018) tasks, were observed as statistically significant here (see Fig. 2). Thus, for the warning signal effect (RT: [F (1, 589) = 601.16, p < .001, η_p^2 = .51]; errors: [F (1, 589) = 160.53, p < .001, η_p^2 = .21]), responses were faster and more accurate in the tone than in the no tone condition. The visual cueing effect (RT: [F (2, 1178) = 877.16, p < .001, η_p^2 = .60]; errors: [F (2, 1178) = 25.90, p < .001, η_p^2 = .04]) showed different benefits for RT and the percentage of errors. As can be observed in Fig. 2, while responses were faster in the valid condition than in the no cue and invalid ones, in the errors analysis responses were more accurate in the no cue than in the valid and invalid conditions. Lastly, the congruency effect (RT: [F (1, 589) = 1104.86, p < .001, η_p^2 = .65]; errors: [F (1, 589) = 9.64, p = .002, η_p^2 = .02]) demonstrated that responses were faster and more accurate in the congruent than in the incongruent condition.

Regarding the differences between the standard and the online ANTI-Vea, there was a significant main effect of task version in RT [F (1, 589) = 12.14, p < .001, η_p^2 = .02], which was not observed in errors (F < 1). Thus, in general, responses were faster in the standard than in the online ANTI-Vea (see Table 3 below). Importantly, the warning signal was significantly modulated by the task version only for RT [F (1, 589) = 23.59, p < .001, η_p^2 = .04], not for errors [F (1, 589) = 2.97, p = .086, η_p^2 = .01]. As can be seen in Fig. 2, the warning signal effect (i.e., no tone minus tone condition) was smaller in the online than in the standard ANTI-Vea. In addition, the modulation of task version over the visual cue (RT: [F (2, 1178) = 4.32, p = .014, η_p^2 = .01]; errors: [F (2, 1178) = 5.43, p = .004, η_p^2 = .01]) demonstrated a smaller cueing effect (i.e., invalid minus valid conditions) for the RT in the online version than in the standard one. Lastly, the interaction between Task version × Congruency was far from statistical significance (both for RT and errors: Fs < 1). Thus, in summary, as it can be observed in Fig.

2, significant and similar indices were observed for the two task versions, although perhaps they were slightly smaller for the alertness and the cueing effect in the online ANTI-Vea.

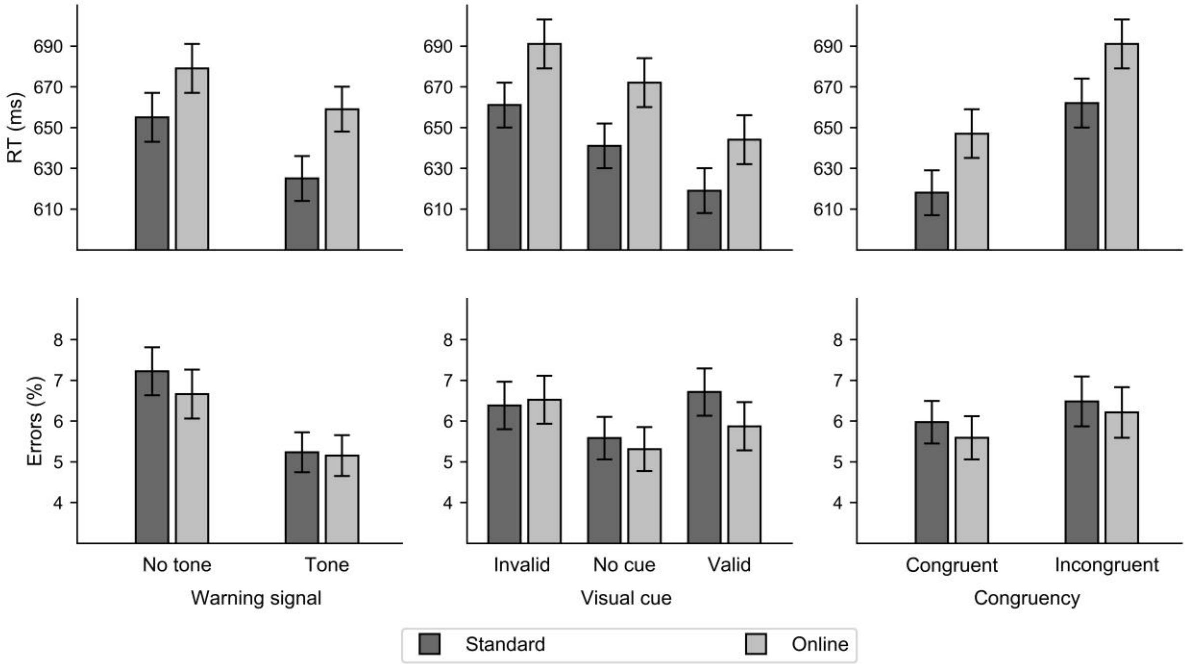

Fig. 2. Mean correct RT (superior graphs) and percentage of errors (inferior graphs) for the warning signal (left), visual cue (center), and congruency (right) conditions, as a function of the task version (standard/online). Error bars represents 95% CI of the mean.

In addition, the typical modulations between the classic attentional functions, usually reported with the ANTI and ANTI-Vea tasks, were also observed as statistically significant here (see Table 2). The interaction between Warning signal × Congruency revealed that, whereas the congruency effect (i.e., incongruent minus congruent trials) was increased by the tone condition with RT [F (1, 589) = 50.76, p < .001, η_p^2 = .08], a very small congruency effect was observed with errors, which was slightly reduced by the tone condition [F (1, 589) = 6.20, p = .013, η_p^2 = .01]. The interaction between Visual cue × Congruency (RT: [F (2, 1178) = 41.90, p < .001, η_p^2 = .07]; errors: [F (2, 1178) = 5.47, p = .004, η_p^2 = .01]) showed that the largest congruency effect was found in the invalid condition, both for RT and errors. Moreover, whereas for the RT the congruency effect was very similar for the no cue and valid conditions, in the analysis of errors the congruency effect was quite reduced in the valid condition in contrast to the no cue one. The interaction between Warning signal × Visual cue (found only for RT: [F (2, 1178) = 122.57, p < .001, η_p^2 = .17]; and not for errors: [F (2, 1178) = 1.56, p = .212, η_p^2 < .01]) showed that the warning signal effect was larger in the no cue condition, than in the invalid and valid ones. Lastly, the interaction between Warning signal × Visual cue × Congruency was observed only in the percentage of errors [F (2, 1178) = 3.48, p = .031, η_p^2 = .01], but not in the RT (F < 1).

Finally, as can be observed in Table 2, task version only modulated the interaction between Warning signal × Visual cue (only for RT: [F (2, 1178) = 6.14, p = .002, η_p^2 = .01]; not for errors: [F (2, 1178) = 2.01, p = .134, η_p^2 < .01]). The remaining interactions between the classic attentional components were not modulated by the task version: Warning signal × Congruency (RT: F < 1; errors: [F (1, 589) = 1.29, p = .257, η_p^2 < .01]), Visual cue × Congruency (RT: [F (2, 1178) = 1.56, p = .209, η_p^2 < .01]; errors: [F (2, 1178) = 1.72, p = .179, η_p^2 < .01]), Warning signal × Visual cue × Congruency (RT: [F (2, 1178) = 2.97, p = .052, η_p^2 = .01]; errors: F < 1).

Table 2. Mean correct RT and errors for warning signal, visual cue, and congruency conditions, as a function of the task version (standard/online).

		Standard				Online			
		Congruent		Incongruent		Congruent		Incongruent	
		M	95% CI	*M*	95% CI	*M*	95% CI	*M*	95% CI
RT (ms)									
No tone	Invalid	644	[632, 656]	691	[679, 703]	671	[659, 683]	719	[707, 732]
	No cue	647	[635, 659]	681	[669, 694]	670	[658, 682]	705	[693, 717]
	Valid	617	[605, 629]	652	[639, 664]	637	[625, 650]	671	[658, 683]
Tone	Invalid	624	[612, 636]	686	[674, 698]	658	[646, 670]	714	[702, 726]
	No cue	593	[581, 605]	641	[629, 653]	634	[622, 646]	678	[666, 690]
	Valid	584	[573, 595]	623	[612, 635]	611	[599, 622]	658	[646, 670]
Errors (%)									
No tone	Invalid	6.76	[5.97, 7.55]	7.88	[6.96, 8.79]	6.17	[5.36, 6.98]	8.04	[7.11, 8.98]
	No cue	6.62	[5.89, 7.36]	7.00	[6.20, 7.79]	5.84	[5.09, 6.59]	6.36	[5.54, 7.18]
	Valid	7.28	[6.51, 8.06]	7.77	[6.91, 8.63]	6.43	[5.64, 7.22]	7.09	[6.21, 7.97]
Tone	Invalid	5.33	[4.64, 6.01]	5.55	[4.77, 6.32]	5.48	[4.78, 6.18]	6.38	[5.58, 7.17]
	No cue	3.92	[3.33, 4.51]	4.80	[4.09, 5.51]	4.25	[3.65, 4.86]	4.80	[4.07, 5.53]
	Valid	5.92	[5.18, 6.65]	5.88	[5.14, 6.61]	5.39	[4.64, 6.14]	4.57	[3.82, 5.32]

Note. M = mean, CI = confidence interval, RT = reaction time.

Executive Vigilance Decrement

The mean RT [*F* (5, 2920) = 5.05, *p* < .001, η_p^2 = .01] and the SD of RT [*F* (5, 2895) = 4.61, *p* < .001, η_p^2 = .01] showed a significant increment across blocks, with a clear linear trend (both for mean [*F* (1, 584) = 12.62, *p* < .001, η_p^2 = .02] and SD of RT [*F* (1, 579) = 18.11, *p* < .001, η_p^2 = .03]). Interestingly, and in line with mean RT in the ANTI trials, it was observed a main effect of task version both for mean [*F* (1, 584) = 6.80, *p* = .009, η_p^2 = .01] and SD of RT [*F* (1, 579) = 8.75, *p* = .003, η_p^2 = .01]. In general, responses were faster in the standard than in the online task, but in contrast, a higher RT variability was found in the standard than in the online version (see Table 3). Importantly, the task version did not modulate the increment across blocks neither for mean nor for SD of RT (both *F*s < 1).

Regarding the analysis of SDT metrics, the EV decrement across time on task was observed in line with previous findings reported with the ANTI-Vea task (Luna et al., 2018). Thus, as shown in Fig 3., we found a significant decrement of both hits [F (5, 2945) = 52.47, $p < .001$, $\eta_p^2 = .08$] (linear trend: [F (1, 589) = 155.48, $p < .001$, $\eta_p^2 = .21$]) and FA [F (5, 2945) = 14.00, $p < .001$, $\eta_p^2 = .02$] (linear trend: [F (1, 589) = 54.53, $p < .001$, $\eta_p^2 = .08$]) across blocks. In addition, there was a significant decrement of A′ [F (5, 2945) = 13.21, $p < .001$, $\eta_p^2 = .02$] (linear trend: [F (1, 589) = 39.85, $p < .001$, $\eta_p^2 = .06$]) and a significant increment of B″ [F (5, 2945) = 26.20, $p < .001$, $\eta_p^2 = .04$] (linear trend: [F (1, 589) = 87.74, $p < .001$, $\eta_p^2 = .13$]) across blocks.

Note that, as observed in Fig. 3, a small main effect of task version was observed both for hits [F (1, 589) = 4.85, $p = .028$, $\eta_p^2 = .01$] and A′ [F (1, 589) = 5.16, $p = .023$, $\eta_p^2 = .01$], but not for FA and B″ (both *F*s < 1). Although it was unexpected, a higher hits rate and A′ was found in the online than in the standard version (see Table 3 below).

In addition, a modulation of task version over the decrement of hits [F (5, 2945) = 2.47, $p = .030$, $\eta_p^2 < .01$] and A′ [F (5, 2945) = 3.10, $p = .009$, $\eta_p^2 = .01$] across blocks was also found. However, in the analysis of the linear component, task version did not modulate neither hits nor A′ across blocks (both *F*s < 1). Thus, it seems probable that the interactions observed between task version and hits/A′ can be mainly due to data in the 3rd block, as shown in Fig. 3. Finally, task version did not modulate FA ($F < 1$) nor B″ [F (5, 2945) = 1.08, $p = .371$, $\eta_p^2 < .01$], thus proving a quite similar EV decrement in the standard as compared to the online version of the ANTI-Vea.

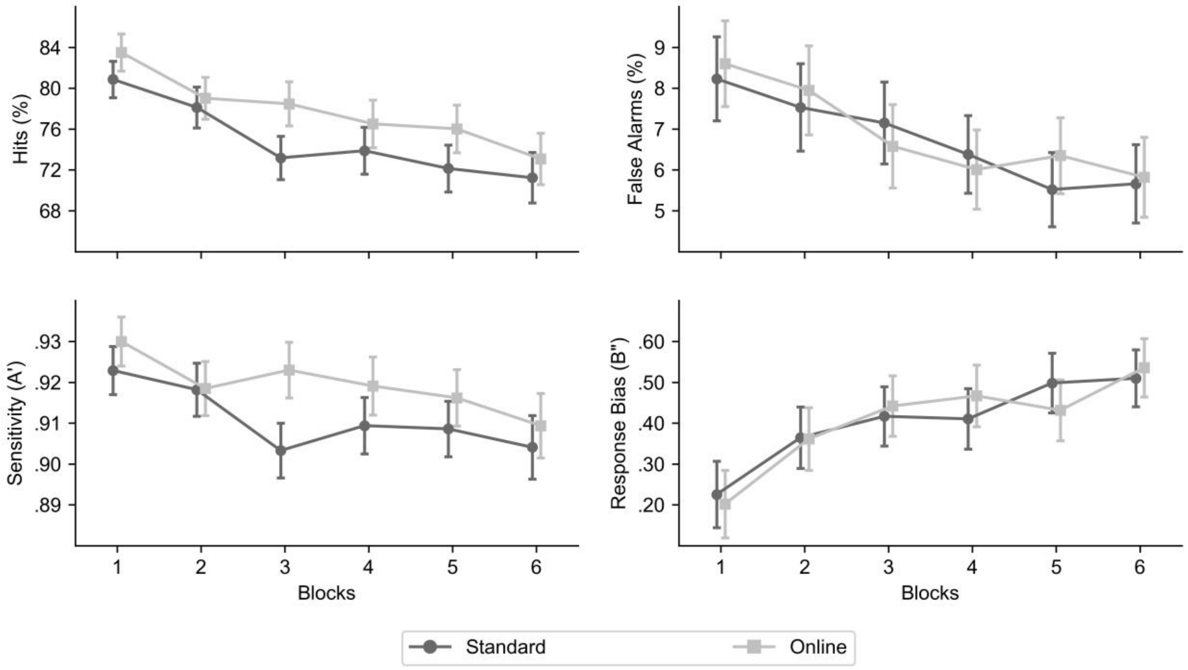

Fig. 3. Executive vigilance decrement as a function task version (standard/online). Graphs shows the percentage of hits (superior left) and FA (superior right), and the indices of sensitivity (bottom left) and response bias (bottom right), per block of trials. Error bars represents 95% CI of the mean.

Arousal Vigilance Decrement

Similar to the EV results, the AV decrement across time on task (see Fig. 4) was found as previously reported with the ANTI-Vea task (Luna et al., 2018). Therefore, a significant increment was observed across blocks for mean RT [F (5, 2945) = 15.08, p < .001, η_p^2 = .02], SD of RT [F (5, 2945) = 26.73, p < .001, η_p^2 = .04] and the percentage of lapses [F (5, 2945) = 39.29, p < .001, η_p^2 = .06]. Importantly, all the dependent variables showed a clear linear trend: mean RT [F (1, 589) = 35.51, p < .001, η_p^2 = .06], SD of RT [F (1, 589) = 76.40, p < .001, η_p^2 = .11], and the percentage of lapses [F (1, 589) = 93.87, p < .001, η_p^2 = .14].

The main effect of task version was clearly observed as significant for mean RT [F (1, 589) = 25.80, p < .001, η_p^2 = .04] and the percentage of lapses [F (1, 589) = 12.54, p < .001, η_p^2

= .02], but not for SD of RT [F (1, 589) = 1.48, p = .225, $\eta_p^2 < .01$]. As observed in Fig. 4, and at difference with mean RT in the EV component, although a similar pattern of data was observed with the two tasks, in general responses were faster and there were fewer lapses in the standard than in the online ANTI-Vea (see also Table 3 below).

Finally, task version showed a marginal modulation over the shift of SD of RT across blocks [F (5, 2945) = 2.26, p = .046, $\eta_p^2 < .01$], which was not observed neither for mean RT nor for lapses (both Fs < 1). Nevertheless, and most importantly, the analysis of the linear component confirmed that the increment of SD of RT across blocks was not different between tasks [F (1, 589) = 2.52, p = .113, $\eta_p^2 < .01$].

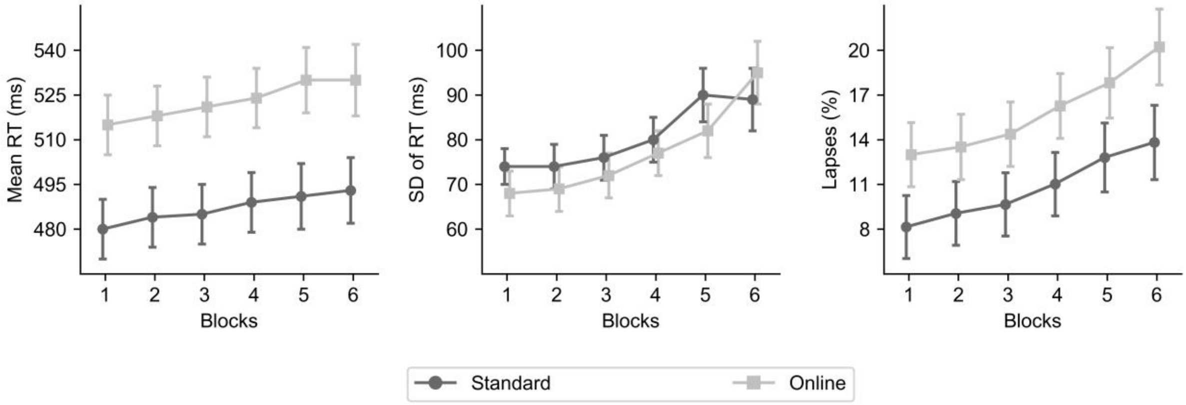

Fig. 4. Arousal vigilance decrement as a function task version (standard/online). Graphs shows the mean RT (left), SD of RT (center), and the percentage of lapses (right), per block of trials. Error bars represents 95% CI of the mean.

Correlations between Attentional Networks and Vigilance Components

Table 3 presents mean indices of the scores computed to analyze the correlations between the different components. For the sake of clarity, the correlations between the classic attentional scores and the vigilance components (EV and AV) are presented in separated tables.

Table 3. Mean and 95% CI for the attentional networks and vigilance indices computed from the standard and online version of the ANTI-Vea task.

	Standard		Online	
	M	95% CI	*M*	95% CI
ANTI - RT (ms)				
Overall	640	[629, 651]	669	[657, 680]
Phasic Alertness	47	[44, 51]	32	[27, 36]
Orienting	42	[39, 46]	46	[43, 49]
Executive Control	44	[41, 48]	44	[40, 47]
ANTI - Errors (%)				
Overall	6.22	[5.68, 6.77]	5.90	[5.42, 6.38]
Phasic Alertness	2.45	[1.88, 3.02]	1.57	[1.02, 2.12]
Orienting	-0.33	[-0.74, 0.07]	0.65	[0.18, 1.11]
Executive Control	0.51	[-0.03, 1.04]	0.61	[0.16, 1.07]
Executive Vigilance				
Mean RT (ms)	744	[735, 752]	762	[752, 773]
SD of RT (ms)	134	[130, 138]	126	[122, 130]
Hits (%)	74.9	[72.98, 76.83]	77.77	[76.09, 79.44]
False Alarms (%)	6.78	[6.11, 7.45]	6.91	[6.20, 7.62]
Sensitivity (A′)	91.17	[90.66, 91.68]	91.97	[91.53, 92.41]
Response Bias (B″)	42.01	[36.89, 47.14]	41.19	[36.22, 46.16]
Arousal Vigilance				
Mean RT (ms)	487	[480, 494]	523	[511, 535]
SD of RT (ms)	88	[84, 93]	87	[83, 91]
Lapses (%)	10.76	[9.14, 12.38]	15.87	[13.51, 18.23]

Note. M = mean, CI = confidence interval, RT = reaction time, SD = standard deviation.

There were no significant correlations between the RT scores of phasic alertness, orienting, and executive control (see Table 4), thus providing additional evidence of the independence between the attentional networks components. Note that, critically, the correlations among the RT scores of the attentional networks were very similar between the standard and the online version of the ANTI-Vea.

Table 4. Pearson's bivariate correlations between the RT scores of the classic attentional networks components, as a function of the task version (standard/online).

	ANTI - Reaction Time (ms)			
	Overall	Phasic Alertness	Orienting	Executive Control
Standard - Reaction Time (ms)				
Overall	-			
Phasic Alertness	.11*	-		
Orienting	.01	.02	-	
Executive Control	.09	.07	-.08	-
Online - Reaction Time (ms)				
Overall	-			
Phasic Alertness	.01	-		
Orienting	.13*	-.09	-	
Executive Control	.05	.09	-.02	-

* *p* < .05, ** *p* < .01, *** *p* < .005, **** *p* < .001

Regarding the correlations among the attentional networks scores computed from the percentage of errors (see Table 5), no significant correlations were found between the classic attentional scores in the standard ANTI-Vea, and only significant but small positive correlations of executive control with phasic alertness and orienting were observed in the online ANTI-Vea.

Table 5. Pearson's bivariate correlations between the percentages of errors' scores of the classic attentional networks components, as a function of the task version (standard/online).

	ANTI - Errors (%)			
	Overall	Phasic Alertness	Orienting	Executive Control
Standard - ANTI Errors (%)				
Overall	-			
Phasic Alertness	.16*	-		
Orienting	-.05	.08	-	
Executive Control	.21****	.01	.01	-
Online - ANTI Errors (%)				
Overall	-			
Phasic Alertness	.15*	-		
Orienting	.08	.08	-	
Executive Control	.18***	.17**	.24****	-

* $p < .05$, ** $p < .01$, *** $p < .005$, **** $p < .001$

With regard to the two vigilance components, note that, as observed in Table 6, EV and AV showed moderate positive correlations between all the RT measures. In addition, only the RT variability of the AV component demonstrated a significant negative correlation with the hit rate and the sensitivity index (A′) of EV, whereas in the remaining measures the EV and AV components showed relative independence. Critically, the correlations between the EV and AV components were observed in the same vein for the standard and online ANTI-Vea versions.

Table 6. Pearson's bivariate correlations between the executive and the arousal vigilance measures, as a function of the task version (standard/online).

	Executive Vigilance					
	Mean RT	SD of RT	Hits	FA	A′	B″
Standard - Arousal Vigilance						
Mean RT	.47****	.22****	-.04	-.11	.00	.10
SD of RT	.31****	.30****	-.20****	-.02	-.22****	.10
Lapses	.45****	.26****	-.03	-.02	-.03	.03
Online - Arousal Vigilance						
Mean RT	.43****	.23****	.09	.00	.09	-.06
SD of RT	.39****	.40****	-.15*	-.06	-.15*	.11
Lapses	.50****	.24****	.10	.06	.07	-.01

Note. RT = reaction time, SD = standard deviation, FA = false alarms.
* *p* < .05, ** *p* < .01, *** *p* < .005, **** *p* < .001

Notably, RT indices of the attentional networks components showed independence with respect to the EV and AV measures (see Table 7), thus providing additional evidence of the independence between attentional and vigilance functions. In particular, the overall RT computed from the ANTI trials positively correlated with all the EV and AV measures, except with the response bias, with which showed a negative correlation. Interestingly, the correlation of the RT measured in the ANTI trials was stronger with the RT measured in EV trials than with the AV ones. In addition, the phasic alertness score showed small positive correlations with the AV measures only in the standard version, but in general (and in line with the previous correlations descripted above), the correlations obtained in Table 7 were very similar for the two task versions.

Table 7. Pearson's bivariate correlations between the RT scores of the classic attentional networks components, and the executive and the arousal vigilance measures, as a function of the task version (standard/online).

	Executive Vigilance						Arousal Vigilance		
	Mean RT	SD of RT	Hits	FA	A′	B″	Mean RT	SD of RT	Lapses
Standard - RT									
Overall (ANTI)	.68****	.45****	.52****	.33****	.43****	-.44****	.39****	.23****	.40****
Phasic Alertness	.05	-.03	-.02	.03	-.04	-.01	.26****	.21****	.22****
Orienting	.01	-.04	.04	.03	.03	-.06	.12*	.02	.13*
Executive Control	.04	.09	-.04	-.13*	.01	.07	-.04	.01	-.04
Online - RT									
Overall (ANTI)	.74****	.55****	.40****	.36****	.23****	-.42****	.31****	.32****	.40****
Phasic Alertness	.06	.00	-.05	-.02	-.05	.03	.08	.07	.08
Orienting	.13*	.07	.06	.04	.04	.01	.05	.01	.03
Executive Control	.05	-.01	-.07	.08	-.10	.02	.02	.11	.03

Note. RT = reaction time, SD = standard deviation, FA = false alarms.
* $p < .05$, ** $p < .01$, *** $p < .005$, **** $p < .001$

Finally, as observed in Table 8, the attentional networks scores computed from the percentage of errors showed significant correlations with the SDT measures in particular – but not with the RT ones – of the EV component, in both the standard and the online ANTI-Vea. In addition, the overall percentage of errors in the ANTI trials positively correlated with the RT variability in the AV component, again in both task versions. Interestingly, it can be observed in Table 8 that, the higher the overall percentage of errors in the ANTI trials, the higher the FA rate. Furthermore, a higher overall percentage of errors in the ANTI trials were associated with a decreased sensitivity and a more conservative liberal response criterion in the EV component. Lastly, the size of the executive control score seems to be negatively related with the percentage of hits, false alarms and sensitivity, but positively with the response bias.

Table 8. Pearson's bivariate correlations between the percentage of errors' scores of the classic attentional networks components, and the executive and the arousal vigilance measures, as a function of the task version (standard/online).

	Executive Vigilance						Arousal Vigilance		
	Mean RT	SD of RT	Hits	FA	A′	B″	Mean RT	SD of RT	Lapses
Standard - Errors									
Overall (ANTI)	.00	.12*	-.04	.64****	-.36****	-.40****	.07	.31****	.17****
Phasic Alertness	-.07	.03	-.12*	.02	-.16**	-.01	.04	.16**	.09
Orienting	-.05	-.02	-.20****	-.23****	-.12*	.21****	.02	.05	.02
Executive Control	-.02	.02	-.29****	-.20****	-.23****	.22****	.01	.06	.01
Online - Errors									
Overall (ANTI)	.04	.11	-.06	.62****	-.42****	-.40****	.00	.30****	.12*
Phasic Alertness	-.04	.03	-.15**	-.06	-.13*	.08	.07	.14*	.06
Orienting	-.10	-.17***	-.21****	-.17**	-.18***	.18***	-.01	.04	.01
Executive Control	-.04	-.11	-.35****	-.24****	-.25****	.29****	-.01	.13*	.00

Note. RT = reaction time, SD = standard deviation, FA = false alarms.
* $p < .05$, ** $p < .01$, *** $p < .005$, **** $p < .001$

Split-Half Reliability Indices

As it can be observed in Table 9, the split-half reliability indices of the classic attentional functions and vigilance components were similar between the standard and the online ANTI-Vea. Note that, in the analysis of the ANTI trials, the reliability was higher in RT than in errors measures. Importantly, only the overall of RT and errors showed a high split-half reliability, i.e., above or very close to .90 when considering the Spearman-Brown prophecy formula. Concerning the classic attentional functions, only executive control demonstrated a moderate coefficient of reliability (i.e., close to .60), whereas the indices obtained for phasic alertness and orienting were very low (i.e., below .40).

Regarding the vigilance components, it can be observed in Table 9 that both versions showed a relative high split-half reliability in all the EV and AV measures. Again, overall RT for EV and AV was found above .90. In addition, the hits rate (EV component) and the percentage of lapses (AV component) also showed a reliability above .90. Lastly, in the EV indices of FA, A′, B″, and the SD of RT in the AV component, the reliability was observed between .76 and .88, with small differences between the standard and the online task version.

Table 9. Mean split-half reliability correlations (r Pearson) for the attentional networks and vigilance components measures. The Spearman-Brown formula extrapolates test-retest reliability from split-half correlations.

	Standard		Online	
	Mean r [95% CI]	Spearman-Brown	Mean r [95% CI]	Spearman-Brown
ANTI - Reaction Time (ms)				
Overall	.98 [.983, .983]	.99	.98 [.984, .984]	.99
Phasic Alertness	.12 [.123, .125]	.22	.22 [.219, .221]	.36
Orienting	.18 [.179, .181]	.31	.18 [.177, .179]	.30
Executive Control	.51 [.508, .510]	.67	.52 [.520, .521]	.68
ANTI - Errors (%)				
Overall	.85 [.845, .846]	.92	.81 [.808, .808]	.89
Phasic Alertness	.10 [.095, .097]	.18	.06 [.060, .062]	.11
Orienting	.03 [.030, .032]	.06	.17 [.164, .166]	.28
Executive Control	.49 [.492, .493]	.66	.36 [.355, .357]	.52
Executive Vigilance				
Mean RT (ms)	.91 [.907, .907]	.95	.94 [.940, .941]	.97
SD of RT (ms)	.58 [.579, .580]	.73	.55 [.553, .554]	.71
Hits (%)	.89 [.890, .891]	.94	.86 [.858, .859]	.92
False Alarms (%)	.74 [.736, .737]	.85	.65 [.650, .651]	.79
Sensitivity (A′)	.79 [.789, .790]	.88	.70 [.700, .701]	.82
Response Bias (B″)	.78 [.780, .781]	.88	.67 [.672, .673]	.80
Arousal Vigilance				
Mean RT (ms)	.95 [.955, .955]	.98	.98 [.983, .983]	.99
SD of RT (ms)	.73 [.730, .731]	.84	.61 [.608, .609]	.76
Lapses (%)	.93 [.926, .926]	.96	.95 [.954, .955]	.98

Note. r = Pearson correlation, CI = confidence interval, RT = reaction time, SD = standard deviation

Discussion

In the present study, we have collected data from a large sample size by measuring the classic attentional functions and both the EV and AV components, either with the standard (i.e., completed in typical lab conditions) or the online (i.e., performed through a website outside the lab) version of the ANTI-Vea task (Luna et al., 2018). By collecting such a large amount of data, we seek to achieve two main goals: (a) to examine whether the online ANTI-Vea is as effective as the standard ANTI-Vea (Luna et al., 2018) to assess both the EV and AV decrement across time on task (Claypoole et al., 2018), along with the main effects and interactions of the classic attentional components; and (b) to examine the split-half reliability of the attentional and vigilance scores obtained by the two versions. Thus, we expected the present study to provide useful evidence for researchers interested in measuring the different components of attention and vigilance, with a reliable method which, importantly, (a) is publicly available in an online website, (b) is easy to use in applied contexts, and (c) is less costly in time and economic resources for collecting data in large sample sizes (Claypoole et al., 2018; Sassenberg & Ditrich, 2019).

For the sake of simplicity, the discussion will be presented as a function of four groups of results: (a) the main effects and interactions of the classic attentional components; (b) the EV and AV decrement across time on task; (b) the independence and correlations between attentional and vigilance components; and (c) the split-half reliability outcomes.

Measuring the Classic Attentional Components in the Lab and Online

The typical main effects usually observed for the classic attentional components with the ANTI (Callejas et al., 2004) and the ANTI-V (Roca et al., 2011), were replicated in the present study for both the standard and the online ANTI-Vea. First, for the orienting network, the facilitation effect of cueing was observed as usual (i.e., valid < no cue < invalid; Posner,

2014) specifically in the RT analysis, whereas in the errors analysis responses were more accurate in the no cue condition than in the valid and invalid conditions. Note that these main effects were observed in the same line for both the standard and the online task (see Fig. 2), and most importantly, the effect size observed for the significant interactions between task version and cueing was indeed very small (i.e., η_p^2 = .01) if considering the large sample size collected. However, it is possible that such difference between the two tasks could be due to the variability of the environmental conditions in which the online task was performed.

Second, for the executive control network, the typical effect of distractors interference usually reported with the flanker task (Eriksen & Eriksen, 1974; Funes et al., 2010) was observed here for both for RT and errors, with no differences between task versions. Note that the size of the interference observed with the ANTI-Vea (i.e., 44 ms in the RT for both task versions, and 0.51% and 0.61% in the errors for the standard and the online version, respectively) seems to be smaller than the one usually reported with the ANTI (Callejas et al., 2004) and ANTI-V (Roca et al., 2011) tasks. To account for this reduced interference, we have recently conducted a separate study to specifically address this issue (Luna, Telga, Vadillo, & Lupiáñez, 2019). In short, and after analyzing data collected from five different experiments, we concluded that, in comparison with the interference effect observed when only performing a flanker task (i.e., ~55 ms and ~3.5% of errors), the concurrent working memory load of performing the flanker and the EV task at the same time: (a) reduces interference (i.e., ~33 ms and ~-0.5% of errors) when the EV task helps to perceptually segregate the target from distractors (i.e., detecting an infrequent vertical displacement of the target, as in the ANTI-Vea); but (b) increases interference (i.e., ~87 ms and ~10.0% errors) when the EV task boosts the perceptual grouping of the target and distractors (i.e., detecting an infrequent horizontal displacement of the target, as in the previous ANTI-V; Roca et al., 2011) (Luna, Telga, et al., 2019).

Regarding phasic alertness, although the typical main effect of warning signal (i.e., faster and more accurate responses in the tone than in the no tone condition; Posner, 2008) was observed with both the standard and the online ANTI-Vea, we found a significant modulation of the task version over the alertness effect in the RT measure. In particular, alertness was slightly reduced (η_p^2 = .04) when the task was administered online as compared to the standard version. It might be possible that, indeed, this would be due to some unknown conditions of the context wherein participants completed the online task, which is usually controlled in an experimental session conducted in the lab (e.g., environmental noise). Furthermore, participants used headphones to hear the auditory tone of warning signal in the lab, while in the online task they were only encouraged to set the sound level of the computer to 75%. These (and other possible factors) could be underlying this unexpected effect, so in future studies, we should control them to better disentangle this reduction of alertness. However, although alertness was slightly reduced in RT when assessed with the online task, note that: (a) in the online ANTI-Vea, indeed, the tone condition significantly improved RT in comparison to the no tone condition [F (1, 288) = 193.14, p < .001, η_p^2 = .40]; and (b) task version did not modulate the alertness effect in the percentage of errors.

Lastly, it was found a significant but small (i.e., η_p^2 = .02) main effect of task version for the overall RT in the ANTI trials, which was not observed for the overall percentage of errors. In general, responses were slower for the online version as compared to the standard one. Again, it is probable that this overall difference in RT between task versions could be due to the variability of the environmental conditions in which the online task was performed. For instance, and as recently stated by Claypoole et al. (2018), in an online session “it is impossible to know whether participants are completing the study cozily in bed or during a chaotic afternoon lecture” (p. 1349). Nevertheless, and critically, note that the typical interactions between the classic attentional components usually reported with the ANTI task (Callejas et al., 2005, 2004) were also observed in the present study, and most importantly, almost all of them were not modulated by the task version. The single significant modulation of task version was observed for the interaction between warning signal and visual cue in RT, which indeed was a very small interaction (i.e., η_p^2 = .01).

Therefore, to sum up, except for the small considerations above-mentioned, the online ANTI-Vea seems to be as effective as the standard ANTI-Vea to assess the main effects and interactions of the classic attentional components.

The Online ANTI-Vea is Suitable to Assess the EV and AV Decrement

One of the main challenges of the present study was to examine whether the vigilance decrement phenomenon, in both the EV and AV component, could be effectively assessed by performing the online ANTI-Vea outside the lab. In this vein, Claypoole et al. (2018) recently argued that some of the main reasons for which only very few studies (Ralph et al., 2015; Sadeh et al., 2011; Thomson et al., 2016) have measured vigilance (and in particular, the EV component) with online tasks might be that: (a) in an online session, experimental conditions cannot be controlled as in the lab and there could be some unexpected factors that might modulate vigilance performance (e.g., it has been demonstrated that mastication helps to reduce the vigilance decrement, see Miquel, Haddou, & Day, 2019; Morgan, Johnson, & Miles, 2014); and (b) as the task would be completed on different devices across participants, it is quite probable that the lack of perceptual uniformity in an online experiment (i.e., as a result of, for instance, different screen sizes or luminosity intensities across the sample) might have an uncontrolled but relevant influence on the vigilance performance (Hashimoto et al., 2003). Notwithstanding, in the same vein as previous online approaches (Fortenbaugh et al., 2015; Ralph et al., 2015; Sadeh et al., 2011; Thomson et al., 2016), we observed in the current study that the online ANTI-Vea is as effective as the standard ANTI-Vea to assess both the EV and AV decrement across time on task.

In particular, for the EV component, in both versions there was a significant and linear decrement on hits and FA across time on task, and as consequence, a linear drop in sensitivity along with a relevant increment in the response bias. Interestingly, it was found a main effect of task version for both the mean and RT variability in the EV task, along with a main effect in the hits and the sensitivity. However, and again, it must be noticed that these main effects seem to be relatively small (i.e., η_p^2 = .01). Most importantly, the linear trends for the different outcomes of the EV decrement were all observed in very similar way for both the standard and the online ANTI-Vea, thus providing consistent evidence that supports the online ANTI-Vea as a suitable method to assess the EV decrement.

Interestingly, note that the EV decrement has been traditionally understood as a significant loss in sensitivity across time on task (See et al., 1995; Warm et al., 2008). However, recently, in a theoretical and empirical demonstration conducted by Thomson et al. (2016), it has been objected that the shift across time in sensitivity and response bias might be biased by a floor effect in the FA, i.e., an effect that is commonly observed in the traditional simple and monotonous signal detection tasks. In particular, Thomson et al. (2016) stated that, to observe the EV decrement as an increment in the response bias rather than as a loss in the sensitivity, then it is imperatively necessary that the drop in hits would be accompanied by a similar drop in FA, something that is highly unlikely to occur if FA are already at the floor in the first period of the task. Therefore, to avoid a floor rate in FA, we decided to compute the FA in the ANTI-Vea only in the ANTI trials wherein it was more probable to observe a FA response (see the Statistical Analyses section), in the same vein that the empirical demonstration conducted by Thomson et al. (2016), and also following the analysis conducted in a separate unpublished study of our lab (Luna, Barttfeld, et al., 2019). Furthermore, and critically, note that the sensitivity-loss effect observed in the present study seems to be indeed dependent on the FA rate observed at the beginning of the task: whereas a significant drop in sensitivity is still observed when FA are at the floor (i.e., equal or lower than 5%) in the first block [F (5, 1215) = 29.56, p < .001, η_p^2 = .11], this effect is not found when FA are higher than 5% in the first block [F (5, 1720) = 1.60, p = .162, η_p^2 = .01].

Regarding the AV component, the decrement across time on task was observed in the same vein as it is usually informed by using the PVT (Basner & Dinges, 2011; Lim & Dinges, 2008), in both the standard and the online ANTI-Vea: there was a significant and linear increment across time on task in the mean and RT variability, as well as in the percentage of lapses. Interestingly, there was a significant main effect of task version for the mean RT and the percentage of lapses, as it was observed in the ANTI and EV components: responses were slower in the online than in the standard ANTI-Vea. As above-discussed, it could be possible that the slowness in RT observed in general (i.e., in the ANTI, EV, and also AV trials) when completing the online version, might be due to unknown conditions from the environment which are generally controlled in a typical experimental session (Claypoole et al., 2018). Furthermore, and critically, the AV decrement was not modulated by the task version, neither in the mean RT, the RT variability (i.e., it was found a very small interaction, with an η_p^2 = .01, that was not confirmed in the analysis of the linear component), nor in the percentage of lapses. Thus, in summary, despite the overall differences observed in mean RT and the percentage of lapses, the AV decrement across time on task was also successfully observed with the online ANTI-Vea as with the standard task.

The Independence and Correlations between Attentional and Vigilance Components

The analysis of bivariate correlations between attentional and vigilance components was driven by three specific research questions regarding the cognitive processes modulated by the attentional networks system: (a) are the classic attentional functions independent among them? (S. E. Petersen & Posner, 2012; Posner & Dehaene, 1994; Posner & Petersen, 1990); (b) are the EV and AV components independent between them? (Luna et al., 2018); (c) is there any association between the classic attentional functions and vigilance components? Note that we have addressed these three issues by measuring the different attentional and vigilance components either in typical experimental conditions or with an online task performed outside the lab. Importantly, and to advance some of the outcomes observed for each task version, most of the significant and non-significant correlation patterns found were very similar between the standard and the online ANTI-Vea.

First, regarding the independence of the classic attentional components, we did not find significant correlations between phasic alertness, orienting, and executive control, neither in RT nor in errors scores (except for the online task, in which some significant but moderate to weak, i.e., < .25, positive correlations were found); a pattern of results that supports the relative independence of the three attentional networks (S. E. Petersen & Posner, 2012; Posner & Dehaene, 1994; Posner & Petersen, 1990). Note that, in previous studies with relative large sample sizes, some significant correlations were observed between attentional components, either with the ANT (MacLeod et al., 2010), the ANTI (Ishigami & Klein, 2010), or the ANTI-V (Roca et al., 2018). However, it should be noted that the scores of the classic attentional components computed with the ANTI-Vea have similar sizes (in particular for the RT measure, where the three scores are around 45 ms). In contrast, the previous versions of the task usually reported different-size scores, particularly for the executive control score, which was quite higher than the phasic alertness and orienting ones (J Fan et al., 2002; Ishigami & Klein, 2010; MacLeod et al., 2010; Roca et al., 2011, 2018). Therefore, it seems that the ANTI-Vea (i.e., both the standard and the online) is a more appropriate task to assess the independence between the classic attentional components (S. E. Petersen & Posner, 2012; Posner & Petersen, 1990), than the previous versions of the task (Callejas et al., 2004; J Fan et al., 2002; Roca et al., 2011).

Second, regarding vigilance, the present study provides novel and consistent evidence to further support an empirical dissociation between EV and AV (Luna et al., 2018). Note that, from a theoretical point of view, the EV component would be specifically implied in selecting a specific response for detecting rare but critical signals over long time periods (Mackworth, 1948; See et al., 1997; Thomson, Besner, et al., 2015), whereas AV would be a component more involved in sustaining a fast reaction to stimuli from the environment without much control over the responses executed (Basner & Dinges, 2011; Lim & Dinges, 2008). Importantly, we have observed in the current study moderate to high (i.e., between .30 and .50) positive correlations between the RT measures of EV and AV. In addition, some small to moderate (i.e., between .15 and .22) negative correlations were observed between both the hits and sensitivity of EV with the SD of RT of AV, which can be interpreted as the lower the RT variability in AV, the higher the ability to detect infrequent signals in EV. However, the main finding (see Table 6) is that, critically, the SDT metrics (i.e., which are indeed the specific measures that describe the ability for detecting infrequent signals) of the EV component seem to be quite unrelated to the RT measures computed for AV, thus supporting (with a large amount of evidence) that vigilance can be considered as two dissociated components.

Finally, the correlation matrices reported in Table 7 and 8 seem to also support a relative independence between the attentional and vigilance components. In particular, the strongest correlation was found between the overall RT of the ANTI and the EV task, which might account for a more general mechanism involved in the speed of responses when executing a specific response. In addition, and importantly, although the EV measures showed moderate to high correlations only with the overall RT of the ANTI task, no significant correlation was observed between SDT metrics of EV and the scores computed for the classic attentional components (except for a negative correlation between executive control and FA which, indeed, seems to be very small, i.e. -.13). Note that, however, in the error analysis, some moderate correlations between the attentional components scores and the SDT metrics of EV were reported. However, again, the strongest correlations observed for SDT metrics of EV were found with the overall percentage of errors of the ANTI task. Thus, it was observed that the higher the errors in the ANTI task: (a) the higher the FA rate, (b) the lower the sensitivity, and (c) the more liberal the response bias, which is a consequence of an increment in the FA rate. Furthermore, although hits did not correlate with the overall percentage of errors in the ANTI task, it was found a negative correlation between hits and the executive control score: it seems that a higher accuracy to select the target from distractors is related with a higher effectiveness for detecting infrequent targets.

With regard to AV, only some moderate to high correlations were observed between the overall RT/errors in the ANTI task and the AV measures, in the same vein than with the EV measures. In addition, and importantly, the phasic alertness score computed in the standard task (which was higher than in the online task) showed a positive correlation with the AV measures. Thus, it seems that the sustained levels of arousal over long time periods (i.e., AV) have a moderate relation with the short increments of arousal (i.e., phasic alertness), which might be part of two different mechanisms of the alerting network (S. E. Petersen & Posner, 2012; Posner, 2008). Therefore, in summary, although we have observed a moderate correlation between the hits of EV and executive control, and between AV and phasic alertness, in general it seems to exist a relative independence between the attentional and vigilance components, which was observed in both in the standard and the online ANTI-Vea task.

The Reliability of the Standard and the Online ANTI-Vea

Although it could be expected that measuring attentional and vigilance components outside the lab would be less reliable, notably, task versions showed very similar reliability for all the scores computed. Note that, critically, the results obtained here replicate previous findings of split-half reliability reported with the ANT (MacLeod et al., 2010) and the ANTI-V (Roca et al., 2018). Thus, for the scores computed with the ANTI trials, we found a high reliability for the overall scores, a moderate to high reliability for executive control, but a relative small reliability for phasic alertness and orienting (MacLeod et al., 2010; Roca et al., 2018). Regarding EV, we found a high reliability for both the RT and the SDT metrics scores, as it was previously observed with the ANTI-V (Roca et al., 2018). Interestingly, note that the reliability of the non-parametric indices of sensitivity and response bias seems to be higher with the ANTI-Vea than the reliability of the parametric indices computed with the ANTI-V task (Roca et al., 2018). Although further analyses might confirm if this difference might be entirely due to the use of parametric or non-parametric indices of SDT (Stanislaw & Todorov, 1999), the findings of the present study can also be interpreted as further evidence that, indeed, the EV measure is more reliable in the ANTI-Vea than in the former version of the task (Luna et al., 2018). Finally, and also importantly, we have observed a high reliability for all the AV measures, again, both in the standard and the online version of the task. Therefore, in summary, we provide here consistent evidence concerning that the ANTI-Vea task (either administered in the lab or in an online session) is highly reliable regarding the assessment of the EV and AV components, and in addition, is at least as reliable as the ANT (MacLeod et al., 2010) and the ANTI-V (Roca et al., 2018) regarding the measurement of the classic attentional components.

Conclusions

The main conclusion of the present study is that the online ANTI-Vea is as effective as the standard ANTI-Vea to assess the main effects and interactions of the classic attentional components, along with the EV and AV decrement across time on task. For researchers interested in administering the online ANTI-Vea outside the lab, it should be noted that slower overall responses and a smaller alertness effect in RT can be observed in comparison to the ANTI-Vea administered in typical experimental conditions. Furthermore, note that the online ANTI-Vea is as suitable as the standard ANTI-Vea to assess: (a) the independence among phasic alertness, orienting, and executive control; (b) the independence between EV and AV; and (c) a relatively strong independence between attentional and vigilance components. Lastly, and importantly, the split-half reliability scores of the online ANTI-Vea are notably similar to the ones computed with the standard ANTI-Vea, which provides further evidence regarding the feasibility of the online task to assess attentional and vigilance components.

Chapter VI

Experimental Series 4

A High-Definition tDCS and EEG study on attention and vigilance: Brain stimulation mitigates the executive but not the arousal vigilance decrement

The content of this chapter is in preparation:

Luna, F.G., Román-Caballero, R., Barttfeld, P., Lupiáñez, J., and Martín-Arévalo, E. A High-Definition tDCS and EEG study on attention and vigilance: Brain stimulation mitigates the executive but not the arousal vigilance decrement

Abstract

Background: Attention comprises a wide set of processes such as phasic alertness, orienting, executive control, and the executive (i.e., detecting infrequent targets) and arousal (i.e., sustaining a fast reaction) vigilance components. Importantly, the effects of transcranial direct current stimulation (tDCS) over attentional functioning have been mostly addressed by measuring these processes separately, and by delivering offline tDCS with low precision over the stimulation region.

Objectives: We examined the effects of online High-Definition tDCS (HD-tDCS) over the behavioral and electrophysiological functioning of attentional and vigilance components.

Methods: Participants (*N* = 92) were randomly assigned to one of three stimulation groups: right dorsolateral prefrontal cortex, right posterior parietal cortex (PPC), and sham. All of them performed – in combination with the HD-tDCS protocol – an attentional networks task (ANTI-Vea) suitable to measure the executive and arousal components of vigilance along with three typical attentional functions: phasic alertness, orienting, and executive control. EEG was registered at the baseline and at the post-stimulation period.

Results: Online HD-tDCS: (a) improved phasic alertness ($p = .008$), but did not modulated the orienting and executive control functioning; and (b) mitigated the executive vigilance decrement ($p = .011$), but did not modulated arousal vigilance. Interestingly, only HD-tDCS over PPC reduced considerably the increment of alpha power across time-on-task ($p = .009$).

Conclusions: The current study provides further evidence for both an empirical dissociation between vigilance components, and the cortical regions underlying attentional processes. We highlight the advantages of using online and HD-tDCS procedures to examine stimulation effects on attentional functioning.

Introduction

Transcranial direct current stimulation (tDCS) has proved to affect attentional functioning in healthy adults (Coffman et al., 2014; Dedoncker, Brunoni, Baeken, & Vanderhasselt, 2016; Reteig et al., 2017). However, although recent studies have demonstrated that anodal tDCS effectively reduces attentional failures in several daily life and work activities such as driving (Sakai, Uchiyama, Tanaka, Sugawara, & Sadato, 2014), staying vigilant in air traffic control operations (J. T. Nelson et al., 2014), or during multitasking activities in military environments (J. Nelson et al., 2016), current evidence is inconsistent, and so the specific effects of anodal tDCS on attentional performance in healthy adults still remain unclear (Coffman et al., 2012; Jacoby & Lavidor, 2018; J. T. Nelson et al., 2014; Roy et al., 2015).

Attentional processes seem to be supported by three independent neural networks, that may interact with each other (S. E. Petersen & Posner, 2012; Posner, 2012b; Posner & Dehaene, 1994; Posner & Petersen, 1990). The alerting network comprises the locus coeruleus along with the right parietal and prefrontal cortices, a set of regions that underlie both phasic alertness (i.e., a brief increment of arousal) and vigilance (i.e., sustaining attention for long time periods) (Posner, 2008). The posterior network involves the pulvinar nuclei of the thalamus, the superior colliculus, the posterior parietal cortex (PPC), and the frontal eye fields, and supports the attentional orienting towards potential relevant sources for stimuli location (Posner, 2014). Finally, the anterior network includes the dorsolateral prefrontal cortex (DLPFC) and the anterior cingulate gyrus, underlying executive control processes to adapt our behavior to long term goals (Shenhav et al., 2013).

The Attentional Network Test (ANT) is a well-known behavioral task to assess the three above-mentioned attentional processes (J Fan et al., 2002). In particular, the effects of anodal tDCS on the ANT performance have been investigated with offline approaches, wherein participants received tDCS at rest, performing the ANT afterword (Coffman et al., 2012; Lo et al., 2019; Roy et al., 2015). However, evidence in this respect is both scarce and ambiguous at best. For instance, 1.5 mA of tDCS during ~20 min over the right PPC significantly improved (Lo et al., 2019) or showed partial effects (Roy et al., 2015) over the orienting network; improvements on phasic alertness were observed only with 2.0 mA of tDCS during ~30 min over the right prefrontal cortex (Coffman et al., 2012); and no modulations over the executive control network were found by tDCS over right PPC (Lo et al., 2019; Roy et al., 2015), right prefrontal cortex (Coffman et al., 2012), or both left PPC and DLPFC (Roy et al., 2015).

Regarding vigilance, some effects of tDCS have been reported as a countermeasure mitigating the performance decrement across time on task (Jacoby & Lavidor, 2018; McIntire et al., 2017; J. T. Nelson et al., 2014; Roe et al., 2016). Note that vigilance has been traditionally assessed by long and monotonous tasks like the Mackworth Clock Test (MCT) (Mackworth, 1948) or the Psychomotor Vigilance Test (PVT) (Basner & Dinges, 2011; Lim & Dinges, 2008) which, nevertheless, seem to assess two different components (Oken et al., 2006; Sarter et al., 2001). The MCT measures an executive component of vigilance, implied in sustaining attention for long time periods to detect infrequent but critical signals (Warm et al., 2008). In this vein, Roy et al. (2015) found that 1.0 mA of 10 min online tDCS over the left DLPFC effectively helps to sustain participants' target detection hits rate across time on task, in contrast to the typical decrement observed with sham tDCS (J. T. Nelson et al., 2014). The PVT assess an arousal component of vigilance, necessary to keep a fast reaction to environmental stimuli without selecting a specific response, a performance usually affected by sleep deprivation (Drummond et al., 2005; Lim & Dinges, 2008). In this sense, after 24 hours of extended wakefulness, 2.0 mA tDCS during ~30 min facilitated a fast reaction time on the PVT in the following six hours, but did not reduce the percentage of lapses (i.e., responses slower than 500 ms), as compared to sham tDCS (McIntire et al., 2014).

The shifts on vigilance performance across time on task seems to correspond with changes in the electrical cortical rhythms (Clayton et al., 2015). In particular, an increment in the alpha band power has been positively associated with psychophysiological states of decreased alertness, as sleep or mental fatigue (Oken et al., 2006). Indeed, Boksem and colleagues found that the vigilance decrement observed in a signal detection task was significantly accompanied by a progressive increment in lower-alpha frequencies (7.5-10 Hz) in the parietal cortex, an effect that was marginal in upper-alpha frequencies (10-12.5 Hz) (Boksem et al., 2005).

The current study had a four-fold goal: (a) to jointly investigate stimulation in two core regions of the attentional networks system, the right PPC and the right DLPFC (S. E. Petersen & Posner, 2012; Posner, 2012b); (b) to measure attentional components by using the Attentional Networks Test for Interactions and Vigilance – executive and arousal components (ANTI-Vea); a novel version which assess simultaneously the three networks along with the decrements in the executive (EV) and arousal vigilance (AV) components (Luna et al., 2018); (c) to increase the precision on the simulation site by using High-Definition tDCS (HD-tDCS) (Datta et al., 2009; Kuo et al., 2013), and to examine the acute effect (i.e., online) (Fertonani & Miniussi, 2017; Yavari et al., 2017) over performance on the ANTI-Vea – at difference to previous offline tDCS studies (Coffman et al., 2012; Jacoby & Lavidor, 2018; Lo et al., 2019; McIntire et al., 2014, 2017; Roy et al., 2015) –; and (d) to inspect the potential effects of HD-tDCS in the alpha power across time on task.

Materials and Methods

Participants

Ninety-two healthy volunteers from the University of Granada participated in the experiment. They had normal or corrected to normal vision, were tested prior to the experiment for exclusion criteria (Rossi, Hallett, Rossini, & Pascual-Leone, 2011), signed an informed consent, and received monetary compensation (10 Euros/hour). The study was conducted according to the ethical standards of the 1964 Declaration of Helsinki (last update: Seoul, 2008), and was part of a larger research project positively evaluated by the University of Granada Ethical Committee (536/CEIH/2018).

Participants were randomly assigned to one of three groups: HD-tDCS over the right PPC (*n* = 32, 24 women, age: *M* = 22.09, *SD* = 3.59), HD-tDCS over the right DLPFC (*n* = 30, 20 women, age: *M* = 23.70, *SD* = 4.28), and sham HD-tDCS, with half of participants being sham-stimulated over the right PPC (*n* = 15, 10 women, age: *M* = 23.20, *SD* = 3.23), and the other half over the right DLPFC (*n* = 15, 9 women, age: *M* = 23.87, *SD* = 3.79).

Stimulation protocols and EEG recording

Apparatus

HD-tDCS procedure and EEG signal recording were controlled with a Starstim® 8 channels wireless system, integrated with the NIC 2.0.10 software application (Neuroelectrics®, Barcelona, Spain). Five hybrid tCS/EEG PiStim (2cm diameter, containing a sintered Ag/AgCl pellet of 12 mm, and ~3.14 cm^2 of contact area) and three standard EEG Geltrode (12 mm diameter, ~1 cm^2 of contact area) circular electrodes were placed over a neoprene headcap with 39 positions based on the International 10-10 EEG system. Electrical reference channels were connected to an EarClip electrode placed over the right earlobe.

HD-tDCS procedure

Electrodes were placed in one of two possible montages: right PPC or right DLPFC (see Fig. 1). Anodal (1.5 mA) or sham (0 mA) HD-tDCS was used respectively depending on the group. In all conditions (real/sham HD-tDCS) we used a 30 sec of ramp up/ ramp down.

Electrodes position, and the voltage field (simulated with ROAST, (Huang, Datta, Bikson, & Parra, 2017)) for the stimulation protocols are depicted in Fig. 1.

EEG data acquisition and pre-processing

In all groups, EEG signal was recorded in channels CP2, P4, PO8, AF4, F4, FC2 (see Fig. 1) along the experiment, although only data from the baseline and post-stimulation block were analyzed. Signal was registered with a sampling rate of 500 Hz, a bandwidth of 0 to 125 Hz, and a notch filter (50 Hz).

EEG data pre-processing was conducted with EEGLAB v14.1.1 toolbox on MATLAB R2016a. Data format was first converted to the EEGLAB format with the NE EEGLAB NIC plugin. To avoid ramp up and down noise effect, analyses were restricted to the first 4:30 min in the baseline block and the last 4:30 min in the post-simulation block. In addition, signal was decomposed using Independent Component Analysis and reconstructed excluding blinks. Frequency filters were set at 0.5 Hz (high pass) and 45 Hz (low pass). Lastly, mean alpha power (i.e., squared signal filtered between 7.5-12.5 Hz) was computed both for the baseline and post-stimulation block.

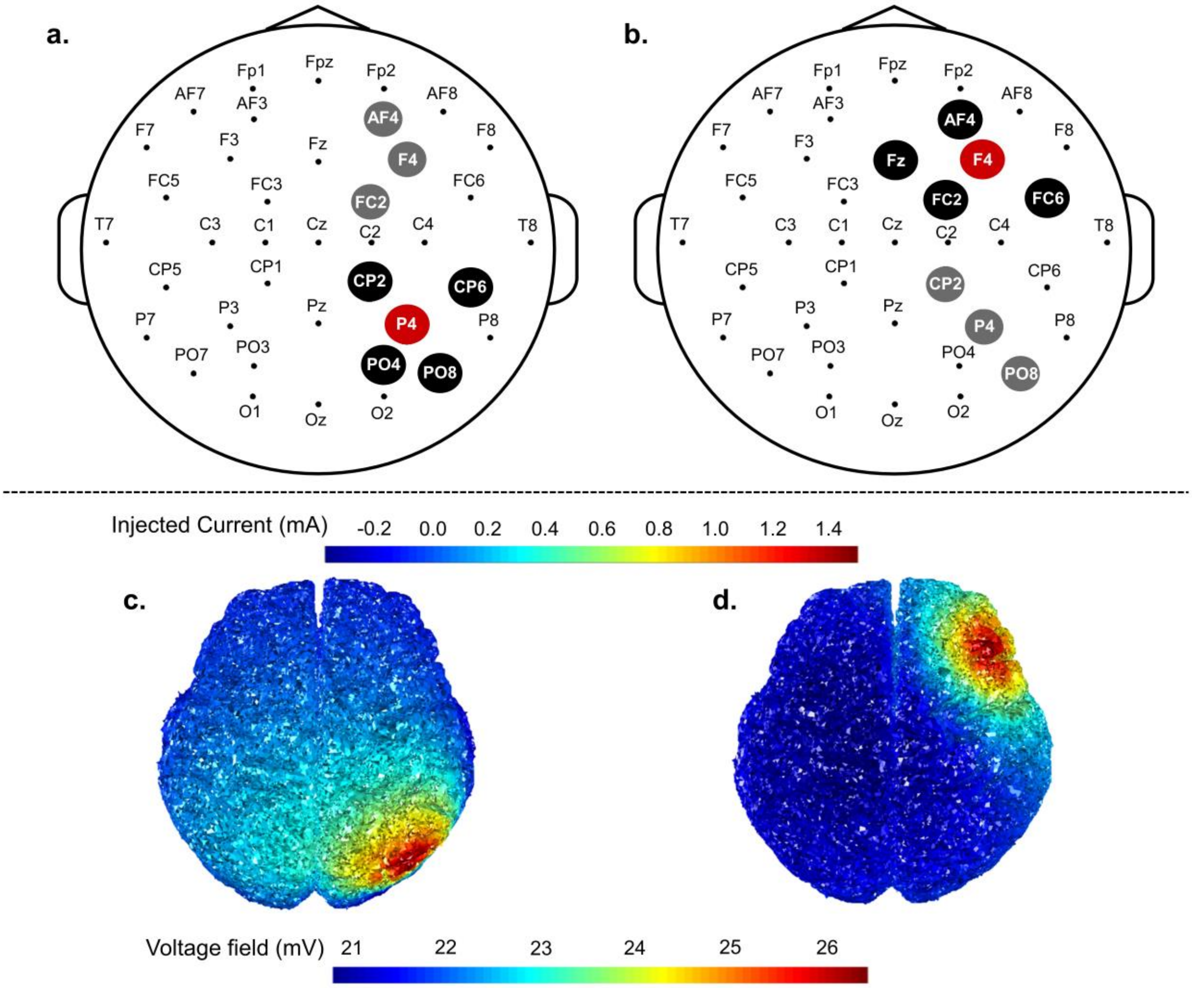

Fig. 1. Electrodes setup and voltage field simulation. The superior panel shows the electrodes setup for (a) HD-tDCS and sham procedures over the right PPC, and (b) the HD-tDCS and sham procedures over the right DLPFC. Electrodes in red delivered anodal (1.5 mA) current in HD-tDCS conditions, and the black electrodes were set as the return ones. Gray electrodes only registered EEG signal. In addition, in the setup shown in (a), CP4, P4 and PO8 also registered EEG at baseline and post stimulation periods, and in the setup shown in (b), AF4, F4, and FC2 registered EEG at baseline and post stimulation periods. The inferior panel shows the simulation of voltage field for (c) HD-tDCS in right PPC and (d) HD-tDCS in right DLPFC.

Behavioral assessment: ANTI-Vea

The task includes three different types of trials (i.e., ANTI, EV, and AV). The stimuli sequence, procedure, and correct responses for each type of trials can be observed in Fig. 2, and are described in detail in Luna et al. (2018). The ANTI trials (see Fig. 2) follows the procedure of the ANTI task (Callejas et al., 2004). Participants had to respond to the direction pointed by a central arrow (i.e., the target), while ignoring the surrounding flanking arrows. The EV trials had the same procedure as the ANTI, except that the target was displaced (i.e., 8 pixels) from its central position either upwards or downwards (see Fig. 2), and participants had to stay vigilant to detect these displaced targets, ignoring in these cases the direction the target pointed to – a task similar to the MCT (Mackworth, 1948). Last, in the AV trials, participants had to stop a millisecond down counter as fast as possible by pressing any keyboard key (see Fig. 2), similar to the PVT (Lim & Dinges, 2008).

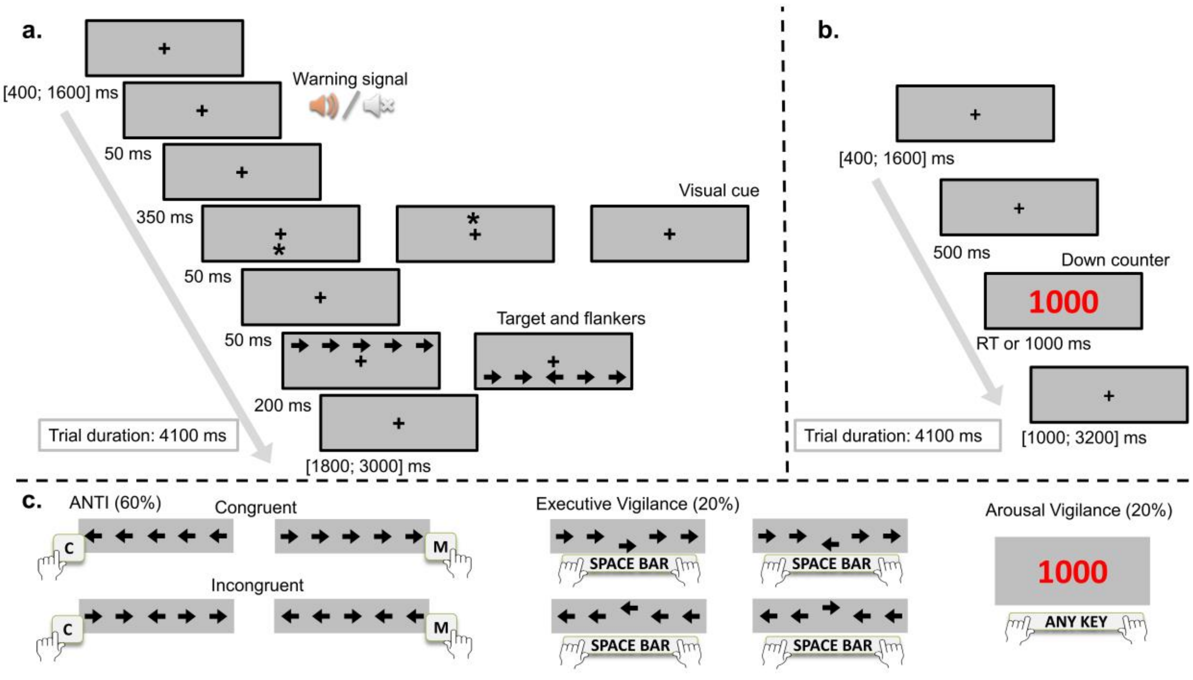

Fig. 2. Stimuli and trials for the ANTI-Vea task. Top panels shows the stimuli sequence for (A) ANTI and executive vigilance trials, and (B) arousal vigilance trials. In the ANTI trials, to assess executive control, the target pointed in a direction either congruent or incongruent with the flanking arrows; to assess phasic alertness, an auditory warning signal anticipated the target

appearance in half of these trials, whereas no warning signal was presented in the other half; and to assess attentional orienting, the arrows position could be preceded either by a valid (i.e., same location) or invalid spatial cue, or by no cue at all. Panel (C) shows the proportion and correct responses for each ANTI, executive vigilance, and arousal vigilance trials.

Procedure

Participants received first the usual specific instructions and practice trials of the ANTI-Vea task by Luna et al. (2018). Then, they completed seven experimental blocks without any pause or feedback, with 80 randomly presented trials in each of them (48 ANTI, 16 EV, and 16 AV). The experimental blocks were divided in three phases: baseline, real/sham stimulation, and post-stimulation (see Fig. 3). At the end of the session, participants completed the Survey of Sensations related to transcranial electrical stimulation (tES)[3] (Fertonani, Ferrari, & Miniussi, 2015).

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[3] Anticipating results from tES, groups did not differ in the self-report of discomfort feelings: all χ^2 comparisons were not significant (all *p*s > .200). In addition, groups did not differ in the perception that discomfort feelings affected their performance [χ^2 (4) = 9.23, *p* = .055], neither in the guessing to the group they belonged to [χ^2 (4) = 2.68, *p* = .612].

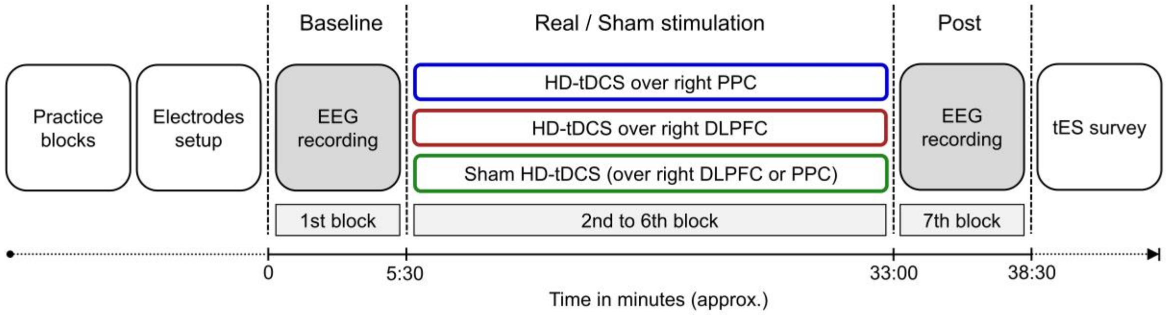


Fig. 3. Session structure. Experimental blocks comprised three different periods: baseline, real or sham stimulation, and post-stimulation.

Statistical Analyses

Behavioral data

Two participants were excluded due to technical problems during data acquisition. The stimulation procedure was included as a between-participants factor, with the following groups: PPC HD-tDCS (n = 31), DLPFC HD-tDCS (n = 29), and sham HD-tDCS (n = 30).

Data from the ANTI trials were analyzed only for the 2nd to 6th block (i.e., during the real/sham stimulation period). In addition, trials with incorrect responses (4.37 %), or with reaction times (RT) below 200 ms or above 1500 ms (1.26 %) were excluded from the RT analysis. Two repeated-measures ANOVAs were conducted, with RT or the percentage of errors as dependent variable, and including warning signal (no tone/tone), visual cue (invalid/no cue/valid), and congruency (congruent/incongruent) as within-participants factors.

To analyze the shifts of vigilance components across time on task, the EV and AV measures were computed per block of trials from the 1st (i.e., baseline) to the 6th block. In the EV trials, we computed the hits (i.e., correct responses on EV trials) and false alarms (FA, i.e., space bar responses in the ANTI trials) rate, and non-parametric indexes of sensitivity (A’) and response bias (B”) (Stanislaw & Todorov, 1999). Following Luna and colleagues, only some

ANTI trials were used to compute FA (Luna, Barttfeld, et al., 2019). The analysis of the EV decrement included four repeated-measures ANOVA, with hits, FA, A’, and B” as dependent variables, and blocks (1st to 6th) as within-participant factor. For the AV trials, the mean and SD of RT were included as dependent variables in the two repeated-measures ANOVA, with blocks (1st to 6th) as within-participant factor. Post-hoc analyses for inspection of HD-tDCS modulations over the EV or AV performance included a one-way ANOVA for the baseline data, and then comparisons to determine the significance of the linear component across blocks.

EEG data

Five participants were additionally excluded either due to technical connection issues during data acquisition (three from the PPC HD-tDCS group) or EEG signal quality (two from the DLPFC HD-tDCS group). Alpha power was analyzed in a repeated-measures ANOVA with group as between-participants factor, and period (baseline/post-stimulation) and region (parietal – the average of CP2, P4, and PO8 data – and frontal – the average of AF4, F4, and FC2 data –) as within-participant factors. Supplementary Fig. 1 presents complementary analyses by channel, and full spectrograms by channel and group.

Results and Discussion

Phasic Alertness, Orienting, and Executive Control

The main effects usually reported with the ANTI (Callejas et al., 2004) and ANTI-Vea (Luna et al., 2018) tasks were replicated here. For warning signal (RT [F (1, 87) = 102.43, p < .001, η_p^2 = .54]; errors [F (1, 87) = 16.15, p < .001, η_p^2 = .16]), responses were faster and more accurate in the tone (RT: M = 568 ms, SE = 10; errors: M = 3.56%, SE = 0.34) than in the no tone (RT: M = 597 ms, SE = 10; errors: M = 5.19%, SE = 0.46) condition. Regarding the congruency effect (RT [F (1, 87) = 301.79, p < .001, η_p^2 = .78]; errors [F (1, 87) = 20.31, p <

.001, η_p^2 = .19]), responses were faster and more accurate on congruent (RT: *M* = 561 ms, *SE* = 10; errors: *M* = 3.61%, *SE* = 0.32) than incongruent (RT: *M* = 605 ms, *SE* = 10; errors: *M* = 5.14 %, *SE* = 0.43) trials. Finally, the cueing effect was only observed for RT ([*F* (2, 174) = 99.33, *p* < .001, η_p^2 = .53]; errors, [*F* (2, 174) = 1.95, *p* = .145, η_p^2 = .02]), with faster responses for valid (*M* = 564 ms, *SE* = 10), than no cue (*M* = 587 ms, *SE* = 10) and invalid (*M* = 597 ms, *SE* = 10) trials.

Additionally, the usual two-way interactions were also replicated: Visual cue × Congruency (RT: [*F* (2, 174) = 8.31, *p* < .001, η_p^2 = .09]; errors: [*F* (2, 174) = 7.23, *p* < .001, η_p^2 = .08]), Warning signal × Visual cue (only for RT [*F* (2, 174) = 25.43, *p* < .001, η_p^2 = .23]; errors: [*F* (2, 174) = 2.11, *p* = .124, η_p^2 = .02]), and Warning signal × Congruency (only for RT: [*F* (1, 87) = 7.58, *p* = .007, η_p^2 = .08]; errors: *F* < 1), providing additional empirical support in favor of the effectiveness of the task to assess both the independency and interactions of the classic attentional functions in the present study (see Table 1 and 2).

A significant main effect of group was observed for RT [*F* (2, 87) = 3.71, *p* = .028, η_p^2 = .08], but not for errors [*F* (2, 87) = 1.03, *p* = .360, η_p^2 = .02]. The PPC HD-tDCS group showed slower RT (*M* = 620 ms, *SE* = 17) as compared to sham (*M* = 565 ms, *SE* = 18) and DLPFC HD-tDCS groups (*M* = 561 ms, *SE* = 16). Note that this effect is unexpected, and likely meaningless, as it was present even in the baseline block [*F* (2, 87) = 4.37, *p* = .016, η_p^2 = .09].

There were no modulations of HD-tDCS over visual cue (RT: *F* < 1, errors: [*F* (4, 174) = 2.18, *p* = .073, η_p^2 = .05]) nor congruency (both for RT and errors: *F*s < 1) effects. Therefore, it might be possible that online HD-tDCS does not effectively modulates orienting, as reported by previous studies with offline tDCS (Lo et al., 2019; Roy et al., 2015). The present results are consistent with previous evidence regarding executive control, wherein no modulation was observed with offline tDCS (Coffman et al., 2012; Lo et al., 2019; Roy et al., 2015).

Interestingly, HD-tDCS significantly modulated the phasic alertness observed for errors [F (2, 87) = 5.13, p = .008, η_p^2 = .11], but not significantly for RT [F (2, 87) = 1.87, p = .161, η_p^2 = .04]. Alertness (i.e., the difference between the no tone and tone condition) was importantly reduced in the PCC HD-tDCS (*M* = 0.59%, *SE* = 0.61) and DLPFC HD-tDCS (*M* = 0.83%, *SE* = 0.59) groups, in contrast to the sham one (*M* = 3.44%, *SE* = 0.87). Note that a specific comparison showed a similar reduction in alertness with RT for the PPC (39 ms) and DLPFC (37 ms) HD-tDCS groups compared to the sham one (55 ms), which was significant specifically at the no cue condition [F (1, 87) = 5.33, p = .023, η_p^2 = .06], wherein alertness is more clearly observed (Callejas et al., 2004). These results indicates a relevant modulation of phasic alertness under real HD-tDCS regardless the stimulation site, in line with previous evidence concerning a modulation of offline tDCS over phasic alertness (Coffman et al., 2012).

Lastly, HD-tDCS did not modulated neither the two-way interactions (both for RT and errors: all *F*s < 1.20, all *p*s > .300), nor the Warning signal × Visual cue × Congruency interaction (RT: [F (4, 174) = 1.41, p = .229, η_p^2 = .03], errors F < 1).

Table 1. Mean correct RT for warning signal, visual cue, and congruency conditions, as a function of HD-tDCS group. SE of mean is shown between parentheses.

		No tone			Tone		
		Invalid	No cue	Valid	Invalid	No cue	Valid
PPC HD-tDCS	Congruent	619 (17)	631 (21)	596 (18)	597 (15)	582 (17)	570 (17)
	Incongruent	665 (18)	659 (16)	639 (21)	650 (16)	630 (17)	606 (17)
DLPFC HD-tDCS	Congruent	554 (17)	565 (16)	535 (17)	541 (18)	521 (16)	514 (19)
	Incongruent	613 (17)	598 (15)	572 (17)	604 (16)	569 (17)	556 (16)
Sham HD-tDCS	Congruent	565 (19)	579 (19)	547 (22)	544 (22)	521 (22)	502 (16)
	Incongruent	611 (19)	622 (21)	579 (16)	601 (19)	568 (18)	552 (17)

Table 2. Percentage of errors for warning signal, visual cue, and congruency conditions, as a function of HD-tDCS group. SE of mean is shown between parentheses.

		No tone			Tone		
		Invalid	No cue	Valid	Invalid	No cue	Valid
PPC HD-tDCS	Congruent	3.06 (0.89)	3.06 (0.68)	6.29 (1.27)	3.06 (0.86)	2.74 (0.76)	5.16 (1.10)
	Incongruent	5.81 (1.11)	4.84 (0.75)	5.48 (1.14)	4.19 (0.90)	5.32 (1.20)	4.52 (1.12)
DLPFC HD-tDCS	Congruent	2.76 (0.84)	2.93 (0.80)	4.14 (0.83)	3.45 (0.96)	1.72 (0.57)	2.59 (0.64)
	Incongruent	6.21 (1.69)	4.48 (0.97)	4.31 (1.16)	5.69 (1.44)	3.62 (0.74)	2.76 (0.73)
Sham HD-tDCS	Congruent	4.67 (1.12)	5.00 (1.15)	6.67 (1.21)	2.50 (0.82)	2.00 (0.82)	3.00 (0.82)
	Incongruent	7.50 (1.31)	8.33 (1.73)	7.67 (1.45)	5.17 (0.94)	3.67 (0.76)	2.83 (1.04)

Executive Vigilance

The main effect of group was significantly observed only for FA [*F* (2, 87) = 5.33, *p* = .007, η_p^2 = .11], but not for hits [*F* (2, 87) = 2.62, *p* = .078, η_p^2 = .06], A’ [*F* (2, 87) = 1.56, *p* = .216, η_p^2 = .03] or B” [*F* (2, 87) = 2.69, *p* = .073, η_p^2 = .06]. The PPC HD-tDCS group made more FA (*M* = 6.01%, *SE* = 0.71) than the sham (*M* = 2.98%, *SE* = 0.72) and the DLPFC HD-tDCS (*M* = 3.36%, *SE* = 0.74) groups.

As can be seen in Fig. 4, the EV decrement was observed as previously reported with the ANTI-Vea task (Luna et al., 2018). There was a significant decrement of hits [F (5, 435) = 12.34, p < .001, η_p^2 = .12] and FA [F (5, 435) = 9.31, p < .001, η_p^2 = .10], and as consequence, a relevant decrement of A' [F (5, 435) = 2.89, p = .014, η_p^2 = .03] and an increment of B" [F (5, 435) = 7.40, p < .001, η_p^2 = .08] across blocks. Note that, interestingly, HD-tDCS modulated the decrement of hits [F (10, 435) = 2.04, p = .028, η_p^2 = .04] and A' [F (10, 435) = 2.04, p = .028, η_p^2 = .04], but not of FA [F (10, 435) = 1.43, p = .164, η_p^2 = .03] and B" [F (10, 435) = 1.12, p = .345, η_p^2 = .03].

Thus, while there was no difference in the hits at baseline between groups [F (2, 87) = 3.06, p = .052, η_p^2 = .07], the expected linear decrement observed in the sham group [F (2, 87) = 24.72, p < .001, η_p^2 = .22], was significantly different compared to that observed in the PPC HD-tDCS [F (1, 87) = 4.54, p = .036, η_p^2 = .05] and the DLPFC HD-tDCS [F (1, 87) = 4.02, p = .048, η_p^2 = .04] groups, which did not differ from each other (F < 1).

Regarding sensitivity, as observed in the hits, groups did not differ on A' at the baseline [F (2, 87) = 1.37, p = .259, η_p^2 = .03]. Moreover, the linear decrement of A' in the sham HD-tDCS group [F (1, 87) = 16.17, p < .001, η_p^2 = .16] was significantly different from that observed in the two HD-tDCS groups [F (1, 87) = 7.53, p = .007, η_p^2 = .08], which did not differ from each other [F (1, 87) = 2.15, p = .146, η_p^2 = .02].

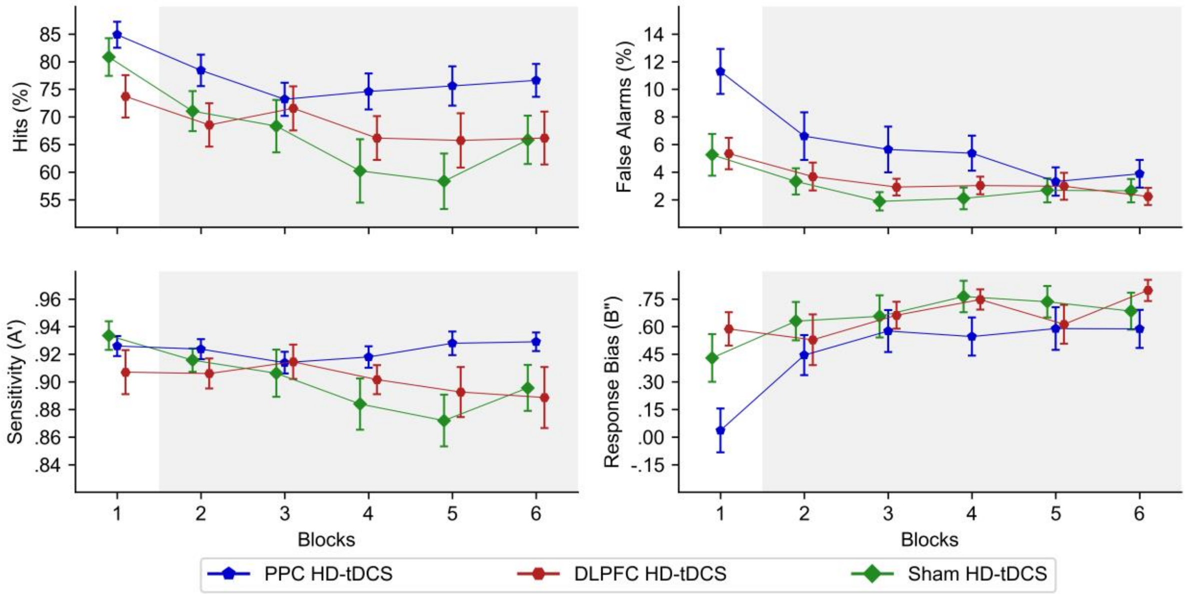


Fig 4. Executive vigilance decrement as a function of HD-tDCS conditions. Graphs represents the hits (superior left), FA (superior right), sensitivity (inferior left), and response bias (inferior right) per block of trials. The shadowed region at each graph denotes the real/sham stimulation period. Error bars shows SE of mean.

Arousal Vigilance

The main effect of group was found as significant for mean RT [*F* (2, 87) = 6.49, *p* = .002, η_p^2 = .13] but not for SD of RT [*F* (2, 87) = 1.90, *p* = .155, η_p^2 = .04]. The PPC HD-tDCS group showed slower responses (*M* = 502 ms, *SE* = 9), than the DLPFC HD-tDCS (*M* = 460 ms, *SE* = 9) and the sham HD-tDCS (*M* = 468 ms, *SE* = 9) groups, a difference observed even in the baseline block [*F* (2, 87) = 4.99, *p* = .009, η_p^2 = .10] and therefore independent of stimulation.

As shown in Fig. 5, the AV decrement was observed as an increment in RT variability across blocks [*F* (5, 435) = 6.54, *p* < .001, η_p^2 = .07], with a significant linear component [*F* (1, 87) = 21.06, *p* < .001, η_p^2 = .19] – a pattern usually observed with the PVT (Basner & Dinges, 2011) and the ANTI-Vea (Luna et al., 2018) –, while mean RT did not change across blocks

(*F* < 1). Importantly, neither mean RT nor RT variability changes across blocks were modulated by the HD-tDCS group (both *F*s < 1).

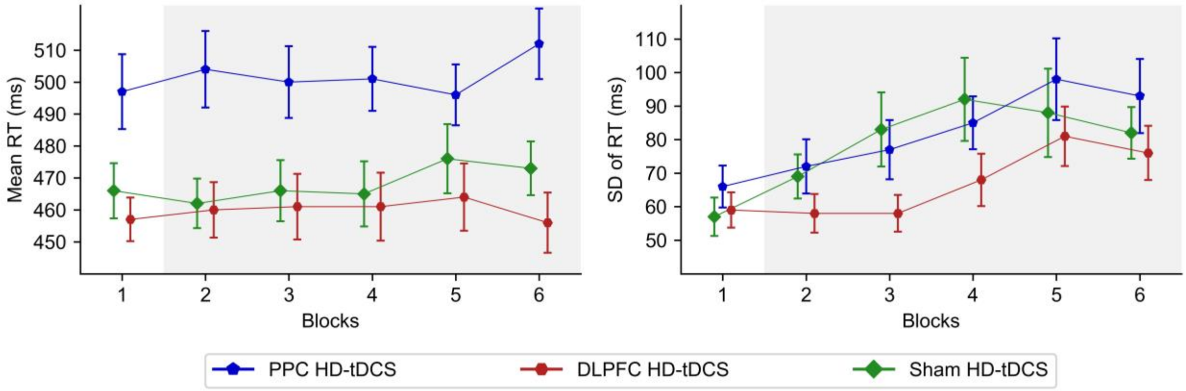


Fig 5. Arousal vigilance decrement as a function of HD-tDCS conditions. Graphs represents the mean RT (left) and RT variability as SD of RT (right), per block of trials. The shadowed region at each graph denotes the real/sham stimulation period. Error bars shows SE of mean.

HD-tDCS modulates differently the EV and AV decrement

PPC and DLPFC HD-tDCS groups were collapsed in one single group and contrasted to the sham group to determine whether HD-tDCS over the two core regions of the attentional networks effectively mitigates only the EV decrement, but not the AV one.

For the EV component, hits showed no main effect of group [*F* (1, 88) = 1.87, *p* = .174, η_p^2 = .02], but a clear significant shift across blocks [*F* (5, 440) = 14.92, *p* < .001, η_p^2 = .14] that was modulated by HD-tDCS [*F* (5, 440) = 3.00, *p* = .011, η_p^2 = .03]. As depicted in Fig. 6, groups did not differ at the baseline (*F* < 1). Most important, the sham group showed a more prominent linear decrement [*F* (1, 88) = 25.01, *p* < .001, η_p^2 = .22], in contrast to the HD-tDCS group [*F* (1, 88) = 8.47, *p* = .004, η_p^2 = .09], which indeed showed no decrement at all within the stimulation period (i.e., from the 2nd to the 6th block: *F* < 1). Therefore, regardless the stimulation site, online HD-tDCS effectively mitigates the EV decrement, supporting previous evidence obtained with online tDCS protocols (J. T. Nelson et al., 2014).

In contrast, AV (measured as the RT variability) showed a considerable increment across blocks [F (5, 440) = 6.20, $p < .001$, $\eta_p^2 = .07$] with a clear linear trend [F (1, 88) = 18.92, $p < .001$, $\eta_p^2 = .18$]. Nevertheless, the RT variability increment was independent of the HD-tDCS group [F (5, 440) = 1.04, $p = .392$, $\eta_p^2 = .01$] (see Fig. 6). Last, there was not a main effect of group for RT variability ($F < 1$). Thus, different from previous evidence obtained with offline tDCS under sleep deprivation conditions (McIntire et al., 2014), here online HD-tDCS did not reduce the AV decrement.

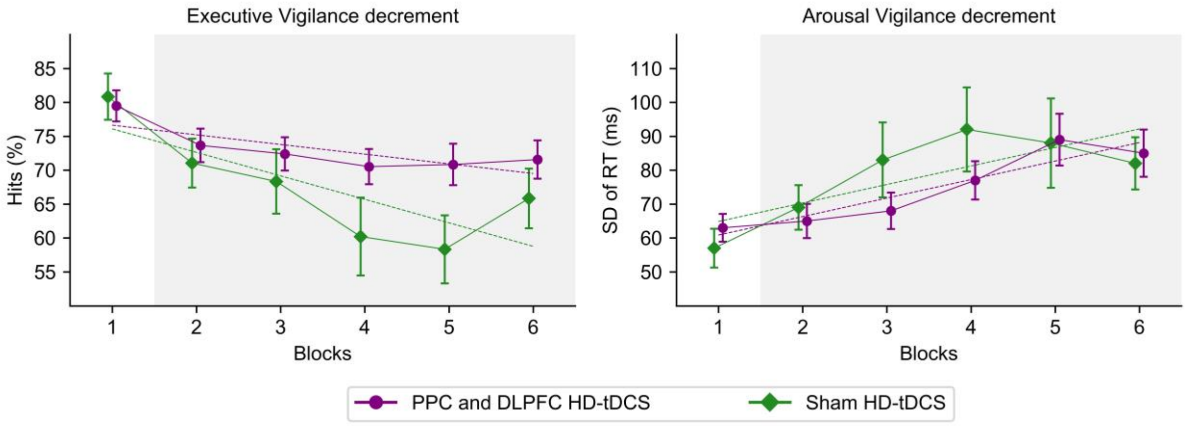


Fig 6. Executive and arousal vigilance decrement as a function of HD-tDCS in the right hemisphere and sham condition. Graphs represents the hits rate (left) and SD of RT (right), per block of trials. The shadowed region at each graph denotes the real/sham stimulation period. Dotted line represents the linear trend for each dependent variable and group. Error bars show SE of mean.

Note that, in an ongoing behavioral study with 617 participants, the linear decrement on the hits [F (1, 589) = 155.48, $p < .001$, $\eta_p^2 = .21$] and the linear increment of AV RT variability [F (1, 589) = 76.40, $p < .001$, $\eta_p^2 = .11$] were consistently observed, with both the standard and an online version (https://www.ugr.es/~neurocog/Sitio_web/ANTI/) of the ANTI-Vea (Luna, Roca, et al., 2019). Importantly, here we have demonstrated that PPC and DLPFC HD-tDCS are effective to moderate only the EV decrement.

HD-tDCS effects on alpha power

Alpha power was not significantly different between groups [*F* (1, 82) = 1.52, *p* = .224, η_p^2 = .04], but there were significant main effects for region [*F* (1, 82) = 51.43, *p* < .001, η_p^2 = .39] and period [*F* (1, 82) = 82.89, *p* < .001, η_p^2 = .50] (see Fig. 7). Thus, in line with previous findings with vigilance tasks (Boksem et al., 2005; Clayton et al., 2015), alpha power was higher over the parietal than over the frontal region, and increased notably from the beginning to the task end.

Most importantly, there was a significant Group × Region × Period interaction [*F* (2, 82) = 4.95, *p* = .009, η_p^2 = .11]. In particular, in the frontal region, alpha power increased significantly between periods [*F* (1, 82) = 69.25, *p* < .001, η_p^2 = .46], with no modulation by group (*F* < 1). Instead, as shown in Fig. 7, in the parietal region alpha power increased differently as a function of group [*F* (2, 82) = 4.27, *p* = .017, η_p^2 = .09], with slighter increment in the PPC [*F* (1, 82) = 4.00, *p* = .049, η_p^2 = .05], than in the DLPFC and sham HD-tDCS groups [*F* (1, 82) = 60.52, *p* < .001, η_p^2 = .42].

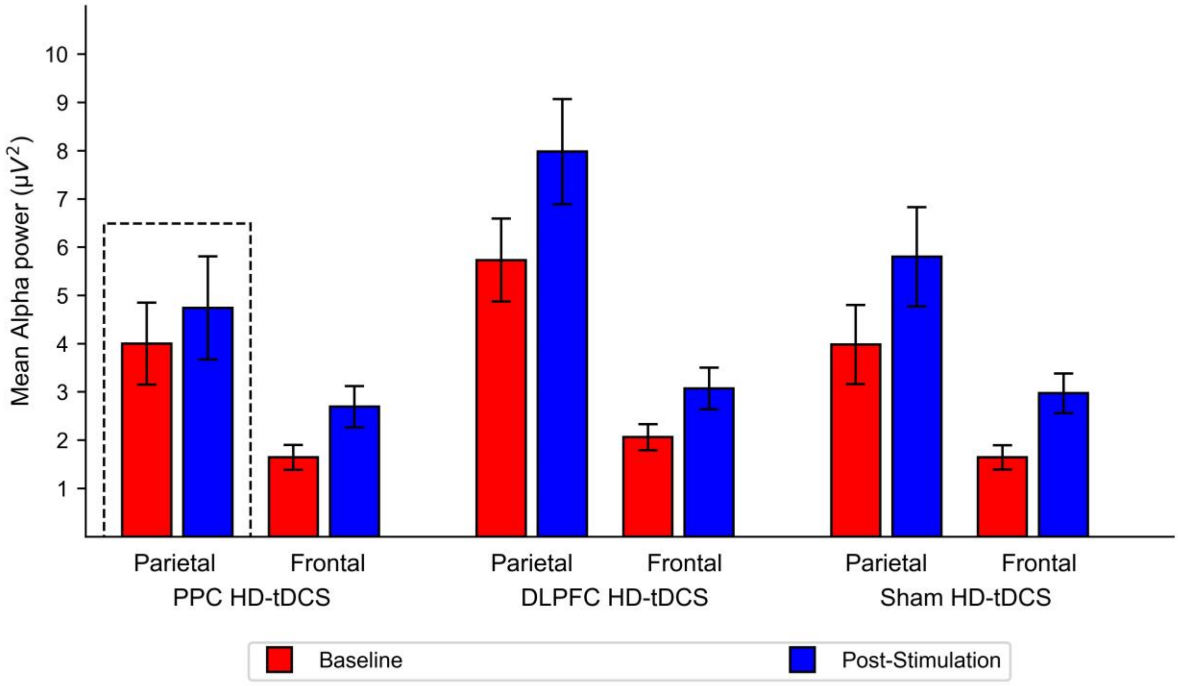
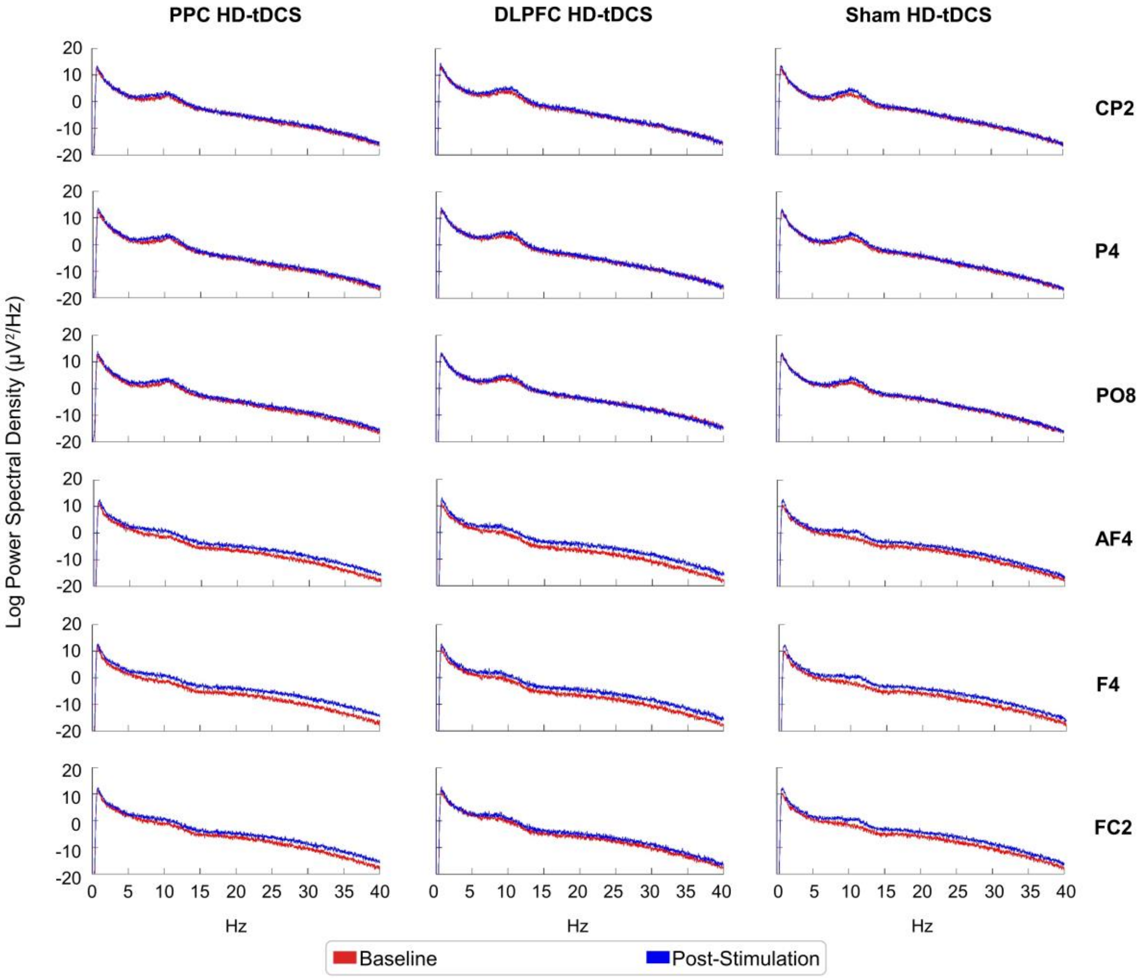


Fig 7. Mean alpha (7.5-12.5 Hz) power by region (parietal: CP2, P4, PO8; and frontal: AF4, FC2, FC2) as a function of period (baseline/post-stimulation) and group (PPC HD-tDCS, DLPFC HD-tDCS, sham HD-tDCS). Note that the most reduced alpha power shift between periods is observed in parietal region of the PPC HD-tDCS group (i.e., the pair of bars within the dotted line). Error bars show SE of mean.

Note that the modulation of PPC HD-tDCS over alpha power seems to be nevertheless independent from performance on the EV and AV components. As reported above, both the PPC and DLPFC HD-tDCS groups showed no decrement on hits within the stimulation period, whereas the reduced increment of alpha power was observed only in the PPC HD-tDCS group. Furthermore, the reduced decrement observed on hits in the two stimulation groups compared to the sham group remained significant [F (5, 410) = 3.36, p = .006, η_p^2 = .04] when the parietal alpha power increment was included as a covariate.

Conclusions

The main contributions of the present study are to have shown that online HD-tDCS over the right PPC and DLPFC effectively: (a) modulates phasic alertness, but not the attentional orienting and executive control functioning, and (b) mitigates the EV decrement, but not the AV one. Critically, the current findings further support an empirical dissociation between vigilance components. Finally, PPC HD-tDCS reduced importantly alpha power increment across time on task, which was however, independent of the vigilance performance.



Supplementary Fig. 1. Full spectrograms (computed with the spectopo function from EEGLAB) as a function of group (PPC HD-tDCS, DLPFC HD-tDCS, and Sham HD-tDCS) and EEG channel. The repeated-measures ANOVA demonstrated a three-way interaction between Group × Channel × Period [F (10, 410) = 2.78, p = .002, η_p^2 = .06] for the alpha power (7.5-12.5 Hz). Pairwise comparisons determined that the increment of alpha power across periods in the PPC HD-tDCS group in contrast to the Sham HD-tDCS one was: (a) significantly smaller [F (1, 56) = 5.35, p = .024, η_p^2 = .09] in the parietal channels (i.e., CP2, P4 and PO8) and (b) not different (F < 1) in the frontal channels (i.e., AF4, F4 and FC2). In addition, alpha power increment across periods was not different between the DLPFC HD-tDCS and the Sham HD-tDCS groups, neither in the parietal (F < 1) nor in the frontal (F < 1) channels.

Chapter VII

Experimental Series 5

Microstructural white matter connectivity underlying the attentional networks system

The content of this chapter is in preparation:

Luna, F.G., Lupiáñez, J., and Martín-Arévalo, E. Microstructural white matter connectivity underlying the attentional networks system

Abstract

Brain activity underlying the attentional networks system (i.e., alerting and vigilance, orienting, and executive control) have been widely examined, but at present there is still a considerable controversy on the structural connectivity underlying attentional networks. In the present study, we aimed at further examining and dissociating the white matter connectivity underlying attentional and vigilance processes. To this end, we performed virtual *in vivo* dissections of attention-related white matter tracts from thirty healthy adults, who performed two sessions of the Attentional Networks Test for Interactions and Vigilance, i.e., a suitable task to assess simultaneously phasic alertness, orienting, executive control, and an executive component of vigilance (i.e., the ability to detect infrequent critical signals). To better analyze the microstructure connectivity in multiple fibers regions, tractographies were reconstructed by using the spherical deconvolution approach, and the Hindrance Modulated Orientational Anisotropy index was used as a proxy for the tract microstructural organization. Whereas we found a consistent correlation between phasic alertness and both the right dorsolateral prefrontal caudate tracts and the splenium of the corpus callosum, the evidence obtained for white matter connectivity underlying orienting, executive control, and executive vigilance, was either weak, inconsistent, or null. Importantly, white matter connectivity seems to support the most reliable performance: whereas overall reaction time for attentional functioning was significantly associated with the left cingulate fasciculus, overall reaction time for executive vigilance was significantly linked to the left and right superior longitudinal fasciculus I. Therefore, whereas the present findings provide interesting evidence concerning the structural connectivity underlying the alerting network, we still consider that much further evidence is necessary to better understand the controversial relationship between attentional/vigilance processes and white matter connectivity.

Introduction

Human attentional networks (i.e., alerting, orienting, and executive control) comprise a wide set of brain circuits supporting attentional performance (S. E. Petersen & Posner, 2012; Posner & Petersen, 1990). To investigate the brain regions involved in attentional networks functioning there has been a growing interest in examining the brain activity (e.g., with functional magnetic resonance imaging and/or electroencephalography) related to attentional performance (Abundis-Gutiérrez, Checa, Castellanos, & Rosario Rueda, 2014; J Fan et al., 2005; Galvao-Carmona et al., 2014; Neuhaus et al., 2010; Xuan et al., 2016). At present, nevertheless, there is still controversy concerning the specific structural connectivity supporting attentional networks circuits in the healthy adults' behavior (Chiang et al., 2015; Niogi et al., 2010; Thiebaut de Schotten et al., 2011). Therefore, in the present study we seek to examine the white matter connectivity underlying the attentional networks functioning (Posner, 2012b; Posner et al., 2006).

According to the conventional model proposed by Posner and collaborators, attentional processes are developed by three relatively independent networks that, nevertheless, may interact with each other (S. E. Petersen & Posner, 2012; Posner & Dehaene, 1994; Posner & Petersen, 1990). The alerting network is regulated by norepinephrine innervations from the locus coeruleus towards parietal and prefrontal cortices of the right hemisphere, a set of regions underlying both phasic alertness (i.e., a brief and momentary increment of arousal) and vigilance (i.e., the ability to sustain attention for extended periods of time; Posner, 2008). The posterior network comprises the superior colliculus and the pulvinar nuclei of the thalamus, along with the frontal eye fields and posterior parietal regions. This network directs attentional orienting over spatial sources from environment to locate potential relevant stimuli (Posner, 2014). Finally, the anterior network mainly involves the anterior cingulate and dorsolateral prefrontal cortices, a circuit that underlies executive control processes to select relevant information from the environment and to adapt out behavior to long term goals (Botvinick et al., 2004; Shenhav et al., 2013).

To analyze and determine the structural brain regions underlying the human attentional networks, there has been a notable and raising interest in the use of Diffusion Weighted Imaging (DWI) (Posner, 2012b; Posner et al., 2006). The reconstruction of whole brain tractography from DWI data acquisition is especially adequate to analyze the structural organization and brain connectivity of white matter tracts (Jones & Leemans, 2011; Le Bihan et al., 2001). Indeed, an often used approach to understand the relationship between white matter tracts connectivity and cognitive functioning is to perform virtual *in vivo* dissections of brain fasciculus of interest (Catani & Thiebaut de Schotten, 2008), and then to correlate offline the indices of white matter connectivity with performance scores (Posner et al., 2006).

In particular, a classical informative index regarding the diffusion directionality of the molecules within the fibers is the fractional anisotropy (FA), which ranges from 0 (isotropic diffusion) to 1 (anisotropic diffusion) (Le Bihan et al., 2001). In general, it has been reported that the higher the fractional anisotropy, the higher the connectivity between the brain regions and thus the cognitive performance (Le Bihan et al., 2001; Soares, Marques, Alves, & Sousa, 2013). However, one of the major limitations of the FA is that represents average measures of tissues properties. Thus, for voxels containing more than one fiber populations, the FA is no fiber-specific. Most recent spherical deconvolution methods have been developed to resolve this multiple fiber orientations limitation (Dell'Acqua et al., 2013) and to improve tractography reconstructions, although its use has not been extensively explored yet.

Thus, as example, the links between white matter connectivity and attentional networks functioning have been mainly addressed by using the FA index. Niogi, Mukherjee, Ghajar, & McCandliss (2010), for instance, measured phasic alertness, orienting, and executive control performance by using the Attentional Networks Test (ANT; Fan, McCandliss, Sommer, Raz, & Posner, 2002), and observed three pairs of positive and independent correlations between: (a) the left posterior limb of the internal capsule (PLIC) and phasic alertness, (b) the splenium of the corpus callosum (CC) and attentional orienting, and (c) the anterior corona radiata and executive control. Regarding vigilance, it has been found that the sensitivity to detect infrequent critical targets across time on task in the Continuous Performance Test (Conners, 2000) shows a positive correlation with the FA of the right cingulate fasciculus (Takahashi et al., 2010). Furthermore, a different role of the left and right dorsolateral prefrontal caudate (DLPFC) tract was also observed for different attentional functions: whereas the left DLPFC seems to be involved in executive control processes, the right DLPFC tract was strongly associated with vigilance performance (Chiang et al., 2015).

Furthermore, and importantly, by reconstructing DWI data with the most sensitive spherical deconvolution approach, Thiebaut de Schotten et al. (2011) were able to disentangle that the classical white matter tracts related to the right visuo-spatial attentional network would correspond to the superior portions of the arcuate fasciculus: the superior longitudinal fasciculus (SLF) branches I, II, and III (Makris et al., 2005). In particular, the SLF I would be linked to the dorsal network proposed by Corbetta, Patel, & Shulman (2008), which connects dorsal prefrontal and posterior parietal cortices and is involved in voluntary orienting of spatial attention towards target stimuli. The SLF III would be overlapped with the right-lateralized ventral fronto-parietal network of Corbetta et al. (2008), underlying the automatic capture of spatial cues. Lastly, the SLF II would be a white matter tract overlapping the dorsal prefrontal regions of the SLF I and the parietal regions of the SLF III (Chica, Bartolomeo, & Lupiáñez, 2013; Thiebaut de Schotten et al., 2011).

In the present study, we aimed at further dissociating the brain regions underlying the structural connectivity of attentional networks (S. E. Petersen & Posner, 2012; Posner et al.,

2006) by using this highly sensitive spherical deconvolution approach (Dell'Acqua et al., 2013). To achieve this goal, we correlated offline data from: (a) virtual *in vivo* dissections of white matter tracts previously reported as related to attentional performance (Chiang et al., 2015; Niogi et al., 2010; Takahashi et al., 2010; Thiebaut de Schotten et al., 2011), and (b) performance scores computed from the ANT for Interactions and Vigilance (ANTI-V; Roca, Castro, López-Ramón, & Lupiáñez, 2011), a behavioral task suitable to assess the independency and interactions of the classic attentional components (i.e., phasic alertness, orienting, and executive control) along with an executive component of vigilance (EV), i.e., the maintenance of attention over long time periods for detecting rare but critical signals. We expect the present study to contribute to a better understanding of the white matter connectivity underlying the human attentional networks (S. E. Petersen & Posner, 2012; Posner, 2012b; Posner et al., 2006).

Method

Participants

A total of thirty volunteers (16 women, age: *M* = 18.57; *SD* = 4.12), who were undergraduate students from the University of Granada, Spain, participated in the study in exchange for a monetary compensation (10 Euros/h). They signed an informed consent approved by the local ethics committee, and completed a safety protocol for magnetic resonance imaging data acquisition. All the participants had normal or corrected to normal vision, and none of them had a history of neurological illness. The study was conducted according to the ethical standards of the 1964 Declaration of Helsinki (last update: Seoul, 2008), and was part of a larger research project, which had been positively evaluated by the University of Granada Ethical Committee (PSI2014-52764-P).

Diffusion Weighted Imaging

Data acquisition

DWI analyses were performed following previously reported procedures (Catani & Thiebaut de Schotten, 2008, 2012; Chiang et al., 2015; Niogi et al., 2010; Thiebaut de Schotten et al., 2011). A total of 70 near-axial slices were acquired on a Siemens 3-TRIO TIM system – equipped with a 32-channel head coil – using a sequence fully optimized for DWI of white matter (based on Damped Richardson Lucy Spherical Deconvolution; Dell'Acqua, Simmons, Williams, & Catani, 2013), providing isotropic (2×2×2 mm) resolution and coverage of the whole head with a posterior-anterior phase of acquisition (echo time = 88 ms and repetition time = 8400 ms). Note that Damped Richardson Lucy Spherical Deconvolution estimates multiple orientations in voxels containing different populations of crossing fibers (Alexander, 2005; Tournier et al., 2004). At each slice location, 6 images were acquired with no diffusion gradient applied and 60 diffusion-weighted images in which gradient directions were uniformly distributed in space. The diffusion weighting was equal to a b-value of 1500s/mm^2.

Data pre-processing and virtual in vivo dissections

First, and for each slice, diffusion-weighted data were simultaneously registered and corrected for subject motion and geometrical distortion adjusting the gradient accordingly (ExploreDTI; Leemans, Jeurissen, Sijbers, & Jones, 2009). Then, individual dissections were carried out with the software TrackVis (Wang, Benner, Sorensen, & Wedeen, 2007).

The three branches of the SLF (on the left and right hemisphere) were isolated using a multiple region of interest (ROI) approach, as in Thiebaut de Schotten et al. (2011). Parietal ROIs and frontal ROIs were delineated around the white matter, based on the guidelines provided in Thiebaut de Schotten et al. (2011). A no-part ROI in the temporal and the corpus callosum white matter were also used to exclude streamlines of the arcuate fasciculus projecting to the temporal lobe (Rojkova et al., 2016; Thiebaut de Schotten et al., 2011). The two cingulate fasciculus (on the left and right hemisphere) were isolated using an one-ROI approach, as recommended in Catani & Thiebaut de Schotten (2008), with no-part ROI in the corpus callosum white matter. The splenium of the CC was also isolated using an one-ROI approach, based on Catani & Thiebaut de Schotten (2008, 2012). The PLIC (on the left and right hemisphere) were also isolated using a multiple ROI approach, based on Niogi et al. (2010), with no-part ROI in the corpus callosum white matter. Finally, the DLPFC tracts (on the left and right hemisphere) were isolated using a multiple ROI approach, as recommended in Chiang et al. (2015). A ROI in the dorsolateral prefrontal cortex and a ROI in the caudate nucleus were delineated around the white matter, with no-part ROI in the corpus callosum white matter.

The index employed as a surrogate for tract microstructural organization (i.e., mean Hindrance Modulated Orientational Anisotropy – HMOA –; Dell'Acqua et al., 2013) was extracted from each dissected tract. The mean HMOA is defined as the absolute amplitude of each lobe of the fiber orientation distribution (FOD) within a specific white matter orientation, and is considered highly sensitive to axonal myelination, fiber diameter, and axonal density (Dell'Acqua et al., 2013), providing thus specific information about the distinct fibers orientations. Thus, whereas the lowest value (i.e., 0) of HMOA indicates the absence of a fiber, the highest value (i.e., 1) corresponds to a signal that references the highest FOD amplitude that can be realistically detected in a specific white matter orientation (Dell'Acqua et al., 2013). A practical application of the HMOA index is that it can be used to describe the microstructural properties of a single fiber population that are dissected from voxels containing multiple fiber orientations with different tissue properties (e.g., such as the axonal diameter or the degree of myelination; Dell'Acqua et al., 2013).

Behavioral Assessment: ANTI-V

Participants completed two experimental sessions of the ANTI-V task (Roca et al., 2011), one before and the other after brain imaging. The task was designed and run in E-Prime v2.0 Professional (Psychology Software Tools, Pittsburgh, PA), and responses were registered with a standard QWERTY keyboard. The stimuli sequence and timing for the ANTI and EV trials are depicted in Fig. 1, and are described in detail in Roca et al. (2011). In short, in the ANTI trials (i.e., 75%), participants completed a flanker task by responding to the direction the target (i.e., a central arrow) pointed to, while ignoring the surrounding flanking arrows. To assess executive control, in half of these trials the direction of the target pointed to the same direction than distractors (congruent condition), whereas in the other half it pointed to the opposite direction (incongruent condition). To assess phasic alertness, a warning signal could anticipate the response stimuli in half of these trials (tone condition), while no warning signal was presented in the other half (no tone condition). Finally, and to assess attentional orienting, an attention capturing asterisk could be presented above or below the fixation point before the string of arrows. The asterisk could: (a) appear at the same location as the asterisk (1/3 of times, valid cue condition), (b) at the opposite location (1/3 of trials, invalid condition), or (c) not be presented (1/3 of trials, no cue condition). Examples of visual cue and congruency are depicted in Fig. 1.

The EV task was embedded along with the ANTI trials, and it was similar to the one performed in the CPT (Conners, 2000). In short, the EV trials (i.e., 25%) had the same procedure than the ANTI ones, except that the target was horizontally displaced from its central position (either leftwards or rightwards, see Fig. 1) and participants had to detect the large displacement by pressing the space bar while ignoring in these cases the direction pointed by the target.

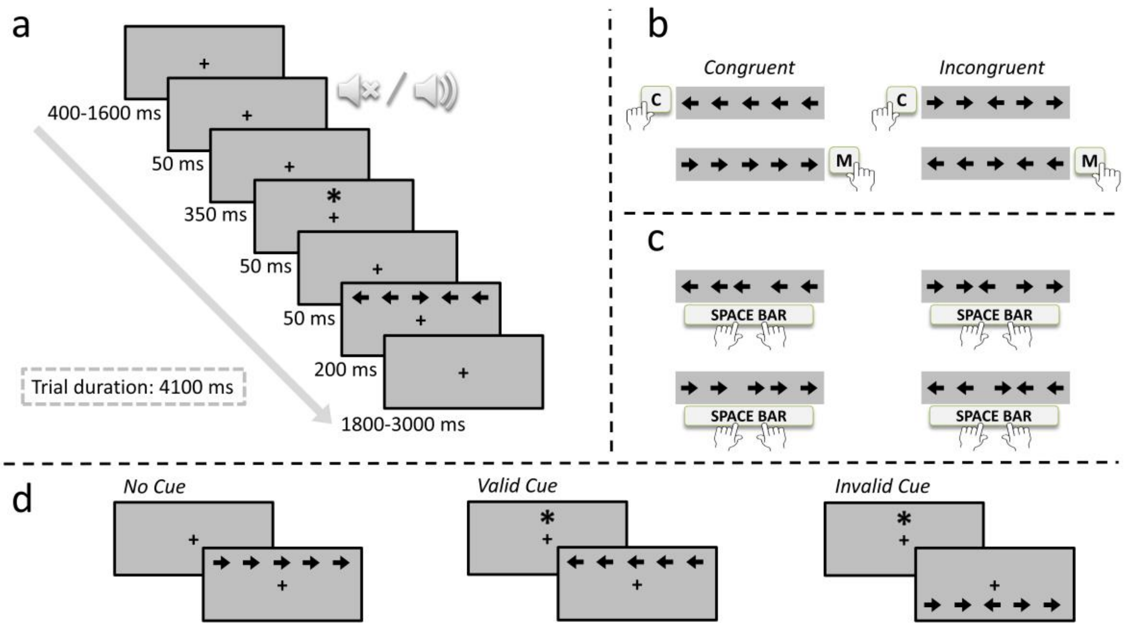


Fig. 1. Procedure and conditions for the trials of the ANTI-V task. (a) Stimuli timing and sequence for both ANTI and EV trials. Responses were allowed until 2000 ms since the target appearance. (b) Examples of congruency conditions. (c) Examples of target displacement in EV trials. (d) Examples of visual cue conditions. Panels (b) and (c) shows the correct response for each type of ANTI and EV trials.

Participants received specific instructions to correctly perform the ANTI-V task, and then they completed one practice block of 48 randomized trials (48 ANTI and 16 EV) with visual feedback. Afterwards, they completed 6 experimental blocks of 64 randomized trials (48 ANTI and 16 EV per block), with no pause or visual feedback. The 48 ANTI trials had the following factorial design: Warning signal (no tone/tone) × Visual Cue (invalid/no cue/valid) × Congruency (congruent/incongruent). The 16 EV trials per block were randomly selected from all the possible trial combinations.

Statistical Analyses

Repeated-measures ANOVA and bivariate Pearson correlations analyses were conducted in Statistica 8.0 (StatSoft, 2007), and JASP v 0.9.0.0 (2018) was used to perform Bayesian correlations. One participant was excluded due to an extreme overall percentage of errors in the ANTI trials (3 *SD* above the group mean), and two participants were additionally excluded due to technical errors in the tractography reconstruction, thus leaving a final sample of twenty-seven participants.

Attentional networks performance

A first analysis examined whether the independency and modulations of attentional networks were successfully observed in the current study. Then, for the ANTI trials, the reaction time (RT) analyses excluded trials with incorrect responses (7.29%), and with RT below 200 ms or above 1500 ms (0.76%). The main effects and interactions of the classic attentional components included two repeated-measures ANOVAs, with RT and the percentage of errors as dependent variable, and including warning signal (no tone/tone), visual cue (invalid/no cue/valid), congruency (congruent/incongruent), and session (two levels) as within-participant factors.

Reliability scores

We then analyzed the test-retest reliability by Pearson's bivariate correlations between sessions. Thus, we computed the attentional networks scores proposed by Callejas et al. (2004) by subtracting average data in specific conditions. The phasic alertness score (i.e., the difference between no tone minus tone conditions) was computed in two different ways: either considering all trials; or only including trials with no visual cue, wherein alertness seems to increase its effect (Callejas et al., 2004), although the measure might be less reliable as it is computed from less observations. For attentional orienting, we computed three different scores: (a) the orienting score as the result of invalid minus valid conditions, (b) the benefits score (i.e., no cue minus valid conditions), which refers to the orienting enhancement obtained from valid visual cues, and (c) the costs score (i.e., invalid minus no cue conditions), as the impairment in orienting as consequence of invalid visual cues. The executive control score was obtained as the difference between incongruent minus congruent conditions. Finally, we computed overall scores for the RT and percentage of errors.

For the EV trials, warning tone, visual cue, and congruency levels were not considered for analyses, with data being collapsed across all these variables. Then, we computed the following signal detection theory metrics: hits (i.e., correct responses in the EV trials) and false alarms (i.e., space bar responses in the ANTI trials) rate, and non-parametric indexes of sensitivity (A') and response bias (B") (J. B. Grier, 1971). Additionally, we obtained the mean and SD of RT on hits, excluding trials with a RT below 200 ms or above 1500 ms (2.02%).

Note that, following MacLeod et al. (2010), a practical interpretation of the reliability based on the test-retest correlations scores might be that: (a) a value smaller than .40 reflects a low reliability; (b) a value between .40 and .60 might be interpreted as moderate reliability; (c) a value between .60 and .70 can be considered as moderate high reliability; and (d) values greater than .70 can be considered as high reliabilities for research purposes.

Correlations between behavioral and DWI data

Bivariate correlations were performed between the HMOA index obtained from virtual *in vivo* dissections, and the overall scores computed across sessions of attentional networks and EV. Note that, importantly, correlations were performed by using two different statistical approaches. While Null-Hypothesis Significance Testing (NHST, i.e., Pearson correlations) were conducted for testing statistical significance (i.e., $p < .05$) to reject the null hypothesis (H_0; i.e., the absence of correlation between variables), Bayesian correlations were performed to test the strength of the evidence supporting either H_0 or the alternative hypothesis (H_1; the existence of a positive or negative correlation between variables) (Jonathon et al., 2018).

For the sake of clarity, note that the inverse Bayes Factor (BF_{10}) computed might be interpreted as following: (a) below 0.33, as consistent evidence in favor for the H_0, (b) between 0.33 and 1, as inconsistent evidence supporting neither the H_0 nor the H_1, (c) between 1 and 3, as weak or anecdotal evidence for the H_1, (d) above 3, as consistent evidence supporting the H_1, in particular: between 3 and 10 as positive or substantial, between 10 a 20 as positive or strong, between 20 and 30 as strong, between 30 and 100 as strong or very strong, between 100 and 150 as strong or decisive, and higher than 150 as very strong or decisive evidence for the H_1 (see Jarosz & Wiley, 2014).

Results

Attentional networks performance

The main effects of the classic attentional components usually reported with the ANTI (Callejas et al., 2004) and ANTI-V (Roca et al., 2011) task were also found significant here (see Table 1). Thus, for warning signal (only for RT [F (1, 26) = 23.23, p < .001, η_p^2 = .47]; and marginal for errors: [F (1, 26) = 4.14, p = .052, η_p^2 = .14]), responses were faster and more precise in the tone than no tone condition. For visual cue (only for RT [F (2, 52) = 53.81, p < .001, η_p^2 = .67]; but not for errors: F < 1), responses were faster in the valid, than no cue and invalid conditions. Finally, for the congruency effect (RT [F (1, 26) = 268.85, p < .001, η_p^2 = .91]; errors: [F (1, 26) = 40.47, p < .001, η_p^2 = .61]), responses were faster and more accurate in the congruent than incongruent condition.

In addition, the two-way interactions usually reported with the ANTI (Callejas et al., 2004) and ANTI-V (Roca et al., 2011) were also found as significant (see Table 1): Warning signal × Visual cue (RT [F (2, 52) = 7.96, p < .001, η_p^2 = .23]; errors: [F (2, 52) = 4.05, p = .023, η_p^2 = .13]), Warning signal × Congruency (only for RT [F (1, 26) = 8.39, p = .008, η_p^2 = .24]; not for errors: F < 1), and Visual cue × Congruency (only for RT [F (2, 52) = 8.54, p < .001, η_p^2 = .25]; errors: [F (2, 52) = 2.11, p = .013, η_p^2 = .08]). This pattern of results further demonstrates that the ANTI-V task was suitable to assess the independency and interactions of the classic attentional components in the current study.

Importantly, as can be observed in Table 1, there was not a significant main effect of session for overall RT and percentage of errors (both *F*s < 1.05, *p*s < .310). Additionally, the experimental session only showed a marginal modulation of the warning signal effect for errors [F (1, 26) = 3.83, p = .061, η_p^2 = .13], but not the main effect for warning signal in the RT, nor visual cue and congruency effects for both RT and percentage of errors (all *F*s < 2.12, *p*s < .130) (see Table 1).

Table 1. Mean correct RT (ms) and percentage of errors for the phasic alertness, visual cue and congruency conditions, as a function of experimental sessions. 95% confidence intervals (CI, lower and upper limits) are represented between brackets.

		Session 1				Session 2			
		Congruent		Incongruent		Congruent		Incongruent	
		M	95% CI	*M*	95% CI	*M*	95% CI	*M*	95% CI
Reaction Time (ms)									
No tone	Invalid	632	[595, 668]	719	[679, 759]	635	[590, 681]	719	[671, 768]
	No cue	639	[603, 674]	712	[673, 752]	640	[592, 688]	704	[660, 748]
	Valid	609	[573, 645]	688	[647, 728]	611	[565, 658]	690	[636, 745]
Tone	Invalid	615	[582, 648]	716	[683, 749]	609	[558, 660]	733	[680, 787]
	No cue	603	[569, 637]	669	[633, 705]	585	[539, 632]	677	[629, 725]
	Valid	588	[556, 620]	675	[634, 717]	570	[527, 614]	651	[604, 699]
Errors (%)									
No tone	Invalid	4.17	[1.62, 6.71]	11.57	[8.11, 15.04]	6.17	[2.90, 9.45]	12.04	[7.97, 16.11]
	No cue	3.55	[1.32, 5.78]	8.95	[5.93, 11.97]	6.48	[3.02, 9.94]	13.12	[8.09, 18.14]
	Valid	4.01	[2.16, 5.87]	9.26	[6.47, 12.05]	6.02	[2.30, 9.74]	10.49	[6.80, 14.19]
Tone	Invalid	1.08	[0.10, 2.06]	9.41	[5.80, 13.03]	4.94	[1.87, 8.01]	9.26	[5.43, 13.09]
	No cue	3.24	[1.23, 5.25]	8.80	[5.27, 12.32]	4.32	[1.45, 7.19]	9.57	[5.86, 13.28]
	Valid	5.56	[2.74, 8.37]	10.49	[7.09, 13.90]	5.71	[2.38, 9.04]	9.26	[5.51, 13.01]

Test-retest Reliability

As can be observed in Table 2, the overall RT of the ANTI trials showed a high reliability score, whereas it was found a moderate reliability for executive control and phasic alertness (only in the RT score computed for all trials), and a low reliability for the orienting scores and the overall percentage of errors, in the same vein that previous studies with the ANT and ANTI-V tasks (MacLeod et al., 2010; Roca et al., 2018). Importantly, moderate to high reliabilities were found for the EV indexes, as previously reported with the split half method for the ANTI-V (Roca et al., 2018), thus proving that the task was suitable to obtain an independent measure of EV across sessions.

Table 2. Attentional and executive vigilance performance scores for each experimental session, the overall across sessions, and the test-retest reliability scores between sessions. 95% Confidence Intervals (CI, lower and upper limits) are represented between brackets.

	Session 1	Session 2	Overall	Test-retest
	M [95% CI]	*M* [95% CI]	*M* [95% CI]	r Pearson
ANTI - Reaction Time (ms)				
Overall	654 [620, 687]	651 [605, 697]	651 [615, 687]	.70****
Alertness	22 [10, 34]	29 [17, 41]	25 [15, 36]	.56***
Alertness (no cue)	39 [22, 55]	40 [21, 60]	39 [23, 55]	.42*
Orienting	29 [21, 37]	43 [33, 52]	36 [30, 42]	.03
Benefits	16 [7, 24]	20 [9, 31]	18 [10, 25]	.24
Costs	13 [2, 24]	22 [11, 34]	18 [10, 26]	.10
Executive Control	82 [70, 94]	87 [75, 99]	85 [74, 95]	.59***
ANTI - Errors (%)				
Overall	6.67 [4.82, 8.53]	8.11 [5.2, 11.03]	7.39 [5.42, 9.37]	.33
Alertness	0.49 [-0.79, 1.77]	1.88 [0.37, 3.39]	1.18 [-0.01, 2.38]	.46*
Alertness (no cue)	0.23 [-1.77, 2.23]	2.85 [0.25, 5.46]	1.54 [-0.36, 3.45]	.36
Orienting	-0.77 [-2.66, 1.12]	0.23 [-1.22, 1.68]	-0.27 [-1.65, 1.11]	.36
Benefits	-1.20 [-3.10, 0.71]	0.50 [-1.08, 2.08]	-0.35 [-1.82, 1.13]	.43*
Costs	0.42 [-1.59, 2.43]	-0.27 [-1.62, 1.08]	0.08 [-1.06, 1.21]	-.13
Executive Control	6.15 [4.45, 7.84]	5.02 [2.66, 7.37]	5.58 [3.78, 7.38]	.57***

Note. *M* = mean, r = Pearson correlation, CI = confidence interval.

* *p* < .05, ** *p* < .01, *** *p* < .005, **** *p* < .001

Descriptive Statistics of White Matter Tracts

Table 3 shows the descriptive statistics of the HMOA index for each of the performed virtual *in vivo* dissections. As a control for the dissections reliability, we compared the HMOA values between hemispheres for well-known lateralized tracks based on previous data (Catani & Thiebaut de Schotten, 2008, 2012; Chiang et al., 2015; Niogi et al., 2010; Thiebaut de Schotten et al., 2011). Thus, supporting previous outcomes (Thiebaut de Schotten et al., 2011), there was a significant lateralization to the right hemisphere for the SLF II [t (26) = 4.95, p < .001] and III [t (26) = 3.32, p = .003] branches, which was not observed for the SLF I [t (26) = 0.20, p = .840]. In addition, and also in the same vein with previous findings (Gong et al., 2005; Takao, Hayashi, & Ohtomo, 2011), the cingulate fasciculus [t (26) = 4.20, p < .001] and the PLIC [t (26) = 5.80, p < .001] were lateralized to the left hemisphere. Lastly, and also in line with previous findings (Chiang et al., 2015), the DLPFC showed no lateralization between hemispheres [t (26) = 1.27, p < .217]. Thus, the usual lateralization pattern of tracks was also observed in our sample with the methods used in the current study.

Table 3. Descriptive statistics of the Hindrance Modulated Orientational Anisotropy index obtained for each white matter tract. 95% Confidence Intervals (CI, lower and upper limits) are represented between brackets.

	HMOA	
	Mean	95% CI
SLF I left	.068	[.064, .072]
SLF I right	.068	[.064, .072]
SLF II left	.083	[.079, .088]
SLF II right	.095	[.091, .099]
SLF III left	.089	[.086, .093]
SLF III right	.093	[.090, .096]
Cingulate left	.124	[.117, .130]
Cingulate right	.113	[.108, .118]
PLIC left	.131	[.127, .134]
PLIC right	.122	[.118, .126]
DLPFC left	.097	[.094, .100]
DLPFC right	.094	[.090, .098]
Splenium CC	.182	[.172, .192]

Note. SLF = superior longitudinal fasciculus, PLIC = posterior limb of internal capsule, DLPFC = dorsolateral pre frontal caudate, CC = corpus callosum, HMOA = Hindrance Modulated Orientational Anisotropy, CI = confidence intervals.

Correlations between Attentional and EV scores and DWI data

For the sake of simplicity, correlations matrices between attentional and EV performance and DWI data are presented in separated tables as a function of the attentional network. For the executive control, as can be observed in Table 4, the significant Pearson correlations observed for both RT and errors scores were not found by the Bayes Factor – at least – as positive evidence in favor of the H_1 (Jarosz & Wiley, 2014). However, as can be also observed in Table 4, it was found a significant negative correlation ($r = -.47$, $p < .05$) between the left cingulate fasciculus and the overall RT, thus meaning that the higher the HMOA of this tract, the faster the responses for the ANTI task. Note that, in this case, this negative Pearson correlation was observed by the Bayes Factor as positive evidence for the H_1 ($BF_{10} = 4.49$).

Table 4. Bivariate Pearson and Bayesian correlations between overall and executive control scores, and the Hindrance Modulated Orientational Anisotropy index of each white matter tract.

	Reaction Time scores				Errors scores			
	Overall		Executive Control		Overall		Executive Control	
	r	BF_{10}	r	BF_{10}	r	BF_{10}	r	BF_{10}
SLF I left	-.18	0.35	-.15	**0.31**	.04	**0.24**	.13	**0.29**
SLF I right	-.18	0.35	-.30	0.71	.12	**0.28**	.19	0.37
SLF II left	-.43*	2.49	-.27	0.57	-.14	**0.30**	.08	**0.26**
SLF II right	.08	**0.26**	.01	**0.24**	-.01	**0.24**	.01	**0.24**
SLF III left	-.15	0.32	-.17	0.34	-.03	**0.24**	.13	**0.29**
SLF III right	.09	**0.26**	.06	**0.25**	-.03	**0.24**	.16	**0.32**
Cingulate left	-.47*	**4.49**	-.27	0.60	-.17	0.33	.07	**0.25**
Cingulate right	-.32	0.84	-.41*	1.95	-.08	**0.26**	.07	**0.25**
PLIC left	-.24	0.48	-.12	**0.29**	.13	**0.30**	.38*	1.52
PLIC right	.07	**0.25**	-.02	**0.24**	.22	0.44	.38*	1.52
DLPFC left	.10	**0.27**	-.41*	1.97	-.01	**0.24**	.12	**0.28**
DLPFC right	-.37	1.30	.03	**0.24**	-.15	**0.31**	-.03	**0.24**
Splenium CC	-.19	0.37	-.05	**0.25**	.18	0.35	.28	0.64

Note. Inverse Bayes factors (BF_{10}) supporting the H_0 (i.e., < 0.33) or the H_1 (i.e., > 3) are in boldface. SLF = superior longitudinal fasciculus, PLIC = posterior limb of internal capsule, DLPFC = dorsolateral pre frontal caudate, CC = corpus callosum, r = Pearson correlation, BF = Bayes Factor.

* $p < .05$, ** $p < .01$, *** $p < .005$, **** $p < .001$

For the phasic alertness, as can be observed in Table 5, the significant negative Pearson correlations between the errors score (computed only from the no cue trials) with the HMOA of the right DLPFC (*r* = -.53, *p* < .005; BF_{10} = 10.44) and the splenium of the CC (*r* = -.54, *p* < .005; BF_{10} = 13.59) were also found as positive to strong evidence for the H_1 by the Bayesian analysis. Moreover, the errors score computed from all trials showed an even stronger significant negative correlation with the splenium of the CC, also observed as strong evidence in favor of the H_1 by the Bayesian analysis (*r* = -.61, *p* < .001; BF_{10} = 54.70). Thus, the higher the HMOA of both the right DLPFC and specially the splenium of the CC, the higher performance under a phasic alertness state. On the other hand, although there was a significant negative correlation (*r* = -.43, *p* < .05) between the RT alertness score computed only from the no cue trials and the left DLPFC, this correlation was observed as weak or anecdotal evidence for the H_1 by the Bayesian analysis (BF_{10} = 2.49). Finally, note that, however, previous correlations found between the left PLIC and phasic alertness (Niogi et al., 2010) were observed in the current study as non-significant correlations that, at the same time, demonstrated to be consistent evidence in favor of the H_0 (for the RT scores), and inconsistent evidence for either the H_0 or the H_1 (for the errors scores).

Table 5. Bivariate Pearson and Bayesian correlations between phasic alertness scores, and the Hindrance Modulated Orientational Anisotropy index of each white matter tract.

	Reaction Time scores				Errors scores			
	Alertness		Alertness (no cue)		Alertness		Alertness (no cue)	
	r	BF_{10}	r	BF_{10}	r	BF_{10}	r	BF_{10}
SLF I left	.06	**0.25**	.08	**0.26**	-.07	**0.25**	-.16	**0.32**
SLF I right	.06	**0.25**	.14	**0.30**	-.19	0.37	-.19	0.37
SLF II left	.09	**0.26**	.09	**0.26**	-.18	0.35	-.19	0.37
SLF II right	.30	0.71	.23	0.45	.11	**0.27**	.08	**0.26**
SLF III left	.24	0.46	.19	0.36	-.10	**0.27**	.10	**0.27**
SLF III right	.37	1.33	.29	0.64	-.10	**0.27**	.08	**0.26**
Cingulate left	.31	0.76	.33	0.89	-.17	0.34	-.23	0.44
Cingulate right	.25	0.51	.25	0.50	-.28	0.63	-.14	**0.31**
PLIC left	.11	**0.28**	.06	**0.25**	-.18	0.35	-.33	0.93
PLIC right	.38	1.48	.24	0.49	.00	**0.24**	-.14	**0.30**
DLPFC left	.38	1.40	.43*	2.49	-.08	**0.26**	-.27	0.56
DLPFC right	-.08	**0.26**	-.02	**0.24**	-.23	0.45	-.53***	**10.44**
Splenium CC	.21	0.40	.32	0.84	-.61****	**54.70**	-.54***	**13.59**

Note. Inverse Bayes factors (BF_{10}) supporting the H_0 (i.e., < 0.33) or the H_1 (i.e., > 3) are in boldface. SLF = superior longitudinal fasciculus, PLIC = posterior limb of internal capsule, DLPFC = dorsolateral pre frontal caudate, CC = corpus callosum, r = Pearson correlation, BF = Bayes Factor.

* *p* < .05, ** *p* < .01, *** *p* < .005, **** *p* < .001

For the orienting network, although it was expected to be associated with both the HMOA of the right SLF III (Thiebaut de Schotten et al., 2011) and the splenium of the CC (Niogi et al., 2010), the few significant Pearson correlations observed in Table 6 in the errors score were not found as positive evidence in favor of the H_1 by the Bayes Factor.

Table 6. Bivariate Pearson and Bayesian correlations between the scores computed for the orienting network, and the Hindrance Modulated Orientational Anisotropy index of each white matter tract.

	Reaction Time scores						Errors scores					
	Orienting		Benefits		Costs		Orienting		Benefits		Costs	
	r	BF_{10}	r	BF_{10}	r	BF_{10}	r	BF_{10}	r	BF_{10}	r	BF_{10}
SLF I left	.02	**0.24**	.03	**0.24**	-.05	**0.25**	-.04	**0.24**	-.29	0.66	.32	0.87
SLF I right	.02	**0.24**	-.20	0.39	.20	0.39	-.23	**0.44**	-.41*	2.10	.26	0.54
SLF II left	-.14	**0.30**	.12	**0.28**	-.21	0.41	.04	**0.24**	-.22	0.42	.33	0.95
SLF II right	-.32	0.86	-.16	0.33	-.09	**0.27**	-.02	**0.24**	-.13	**0.29**	.15	**0.31**
SLF III left	-.23	0.44	-.11	**0.27**	-.07	**0.25**	.07	**0.25**	.03	**0.24**	.05	**0.25**
SLF III right	-.37	1.30	-.21	0.40	-.09	**0.26**	.14	**0.30**	.27	0.59	-.18	0.36
Cingulate left	-.07	**0.25**	-.05	**0.25**	.00	**0.24**	.13	**0.29**	-.02	**0.24**	.18	0.35
Cingulate right	.03	**0.24**	.01	**0.24**	.02	**0.24**	.21	0.41	.00	**0.24**	.26	0.55
PLIC left	-.14	**0.30**	-.04	**0.25**	-.06	**0.25**	.34	1.04	.23	0.44	.12	**0.29**
PLIC right	-.22	0.42	-.23	0.46	.05	**0.25**	.39*	1.60	.07	**0.25**	.38	1.47
DLPFC left	-.29	0.68	-.18	0.35	-.06	**0.25**	-.04	**0.24**	.02	**0.24**	-.08	**0.26**
DLPFC right	-.07	**0.25**	.08	**0.26**	-.12	**0.28**	-.08	**0.26**	-.01	**0.24**	-.08	**0.26**
Splenium CC	-.23	0.44	.16	0.33	-.32	0.86	.02	**0.24**	-.11	**0.28**	.17	0.34

Note. Inverse Bayes factors (BF_{10}) supporting the H_0 (i.e., < 0.33) or the H_1 (i.e., > 3) are in boldface. SLF = superior longitudinal fasciculus, PLIC = posterior limb of internal capsule, DLPFC = dorsolateral pre frontal caudate, CC = corpus callosum, r = Pearson correlation, BF = Bayes Factor.

* $p < .05$, ** $p < .01$, *** $p < .005$, **** $p < .001$

Regarding the scores computed for EV performance, only the overall mean RT in the hits showed a significant negative correlation with the HMOA of the SLF I, both for the left ($r = -.53$, $p < .005$; $BF_{10} = 11.92$) and right ($r = -.50$, $p < .01$; $BF_{10} = 6.67$) hemisphere, with both correlations also observed as positive to strong evidence for the H_1 by the Bayes Factor. Thus, the higher the HMOA of SLF I, the faster the responses for hits on infrequent target detection, with independence of the brain hemisphere. Note that, however, SDT metrics computed for EV did not show any relevant correlation with the HMOA index of the white matter tracts dissected in the current study (see Table 7).

Table 7. Bivariate Pearson and Bayesian correlations between the scores computed for executive vigilance, and the Hindrance Modulated Orientational Anisotropy index of each white matter tract.

	Executive Vigilance scores											
	Mean RT		SD of RT		Hits		False alarms		A'		B"	
	r	BF_{10}	r	BF_{10}	r	BF_{10}	r	BF_{10}	r	BF_{10}	r	BF_{10}
SLF I left	-.53***	**11.92**	-.38	1.43	.15	**0.31**	.28	0.61	.12	**0.29**	-.19	0.37
SLF I right	-.50**	**6.67**	-.34	0.98	.28	0.62	.34	1.00	.23	0.44	-.25	0.51
SLF II left	-.35	1.14	-.26	0.56	-.26	0.53	-.11	**0.28**	-.16	**0.32**	.12	**0.29**
SLF II right	-.03	**0.24**	.16	**0.32**	.08	**0.26**	.09	**0.26**	.04	**0.24**	-.09	**0.26**
SLF III left	-.11	**0.27**	.05	**0.25**	-.24	0.48	.01	**0.24**	-.25	0.50	.01	**0.24**
SLF III right	.08	**0.26**	.20	0.39	-.07	**0.25**	-.05	**0.25**	-.10	**0.27**	.02	**0.24**
Cingulate left	-.20	0.39	-.17	0.33	-.35	1.05	-.11	**0.27**	-.37	1.39	-.03	**0.24**
Cingulate right	.00	**0.24**	.04	**0.24**	-.33	0.95	-.18	0.35	-.27	0.57	.13	**0.29**
PLIC left	-.20	0.38	.05	**0.25**	-.17	0.34	.16	0.33	-.29	0.67	-.25	0.51
PLIC right	-.14	**0.30**	.11	**0.28**	.09	**0.26**	.23	0.46	.04	**0.24**	-.19	0.37
DLPFC left	.01	**0.24**	.21	0.40	.04	**0.24**	.12	**0.28**	-.06	**0.25**	-.18	0.35
DLPFC right	-.29	0.67	-.26	0.52	-.20	0.39	-.05	**0.25**	-.27	0.57	-.09	**0.26**
Splenium CC	-.30	0.74	-.23	0.46	-.07	**0.25**	.17	0.33	-.09	**0.26**	-.08	**0.26**

Note. Inverse Bayes factors (BF_{10}) supporting the H_0 (i.e., < 0.33) or the H_1 (i.e., > 3) are in boldface. SLF = superior longitudinal fasciculus, PLIC = posterior limb of internal capsule, DLPFC = dorsolateral pre frontal caudate, CC = corpus callosum, RT = reaction time, SD = standard deviation, A' = non parametric index of sensitivity, B" = non parametric index of response bias, r = Pearson correlation, BF = Bayes Factor.

* $p < .05$, ** $p < .01$, *** $p < .005$, **** $p < .001$

Finally, it is important to note that Bayesian analysis were useful to examine two critical issues of the correlations performed between HMOA and the attentional/vigilance scores, which were indeed unable to address by the NHST approach. On the one hand, the inverse Bayes factor demonstrated that a large pattern of correlations (either unexpected or expected on the basis of previous research) were observed as consistent evidence to support the H_0, i.e., an absence of correlation. For instance, whereas Niogi et al. (2010) found a positive and significant correlation between the left PLIC and the RT score of phasic alertness, this correlation was observed in the current study for both RT scores of phasic alertness with a $BF_{10} < 0.33$ (see Table 5, but also others correlations with a similar BF_{10} in Tables 4, 5, 6, and 7). On the other hand, note that a small but interesting set of results, regardless to be found significant or non-significant by the Pearson correlation, were observed by Bayesian analyses as weak or anecdotal evidence in favor for the H_1, e.g., the correlations between: (a) the left DLPFC and the RT score of executive control, which was previously reported by Chiang et al. (2015), was observed here with a $BF_{10} = 1.97$ (see Table 4); or (b) the right SLF III and the RT orienting score, an association critically discussed by Thiebaut de Schotten et al. (2011) and Chica et al. (2013), was observed in the present study with a $BF_{10} = 1.30$ (see Table 6). Therefore, it seems that larger amount of evidence is necessary to further determine whether the correlations observed as weak or anecdotal evidence in favor of the H_1 can be effectively supported at least as positive evidence for the H_1 by the Bayesian analysis.

Discussion

The main goal of the present study was to provide further evidence to dissociate the structural brain connectivity underlying attentional networks in healthy adults. To this end, we correlated offline the performance scores of the classic attentional components and EV obtained across two experimental sessions with the ANTI-V task (Roca et al., 2011), with the microstructure connectivity of white matter tracts previously associated with attentional performance (Chiang et al., 2015; Niogi et al., 2010; Takahashi et al., 2010; Thiebaut de Schotten et al., 2011). Importantly, note that the methodological procedure and statistical analyses conducted in the current work aimed at solving some limitations observed in previous researches. First, we used a fine-grained behavioral paradigm that provides in a single session an independent measure of the classic attentional components and EV: the ANTI-V (Roca et al., 2011). Furthermore, we reconstructed DWI data with the spherical deconvolutions approach (Alexander, 2005; Tournier et al., 2004), a methodology that is much sensitive for dissecting white matter tracts that are embedded in brain regions with crossing fibers, as the branches I, II, and III of the SLF (Thiebaut de Schotten et al., 2011). Therefore, we computed the HMOA index for analyzing white matter connectivity, which is indeed more appropriate for measuring the diffusion properties in white matter regions with a complex organization, than traditional indices as the FA or mean diffusivity (Dell'Acqua et al., 2013). Lastly, we used two statistical analyses to interpret the outcomes: whereas Pearson correlations were computed to analyze the evidence supporting a rejection of the null hypothesis (i.e., there is no correlation between performance scores and white matter connectivity), we also computed Bayesian correlations for analyzing the evidence collected for supporting either the H_0 or the H_1.

Importantly, the main effects and interactions for the classic attentional components and the EV indices (Callejas et al., 2004; Roca et al., 2011), the test-retest reliability of performance scores (MacLeod et al., 2010; Roca et al., 2018), and the hemispheric lateralization (if any) of white matters tracts (Chiang et al., 2015; Gong et al., 2005; Takao et al., 2011; Thiebaut de Schotten et al., 2011), were observed in the same vein than previous outcomes, somehow validating our methods and the observed correlations between performance scores and white matter connectivity.

With regards to the correlations between HMOA and the attentional/vigilance performance, it is important to note that some correlations that were found as significant by NHST, were indeed not observed at least as positive evidence in favor of the H_1 by the Bayes factor (e.g., the RT phasic alertness score from no cue trials with the left DLPFC). In addition, there were also some non-significant correlations that showed a BF_{10} between 1 and 3, thus suggesting only weak or anecdotal evidence to the H_1 (e.g., the RT orienting score with the right SLF III). Therefore, it might be possible that the existence of these significant and non-significant correlations would be effectively determined by collecting a larger sample size than the one of the present study, to therefore gather a much larger amount of evidence (Masson, 2011).

Thus, in summary, taking into consideration the results obtained as significant by both Pearson correlations, and at least as positive evidence for the H_1 by the Bayesian correlations, the main findings of the present study are that: (a) higher values of HMOA in the left cingulate fasciculus are associated with faster overall responses in attentional networks performance; (b) higher HMOA indices in the right DLPFC and the splenium of the CC are related to an improved accuracy under a phasic alertness state; (c) higher HMOA indices in both left and right SLF I are associated with faster responses for the correct detection of infrequent signals in EV performance; and (d) critically, no relevant correlations were observed for overall percentage of errors in the ANTI trials, the orienting scores, the executive control performance, or the SDT metrics computed for EV.

It is interesting to note that two of the three scores that showed relevant correlations with white matter tracts connectivity were the overall RT for the attentional networks performance (i.e., ANTI trials) and the overall RT for the EV task, which are indeed the most reliable performance scores usually observed with the ANT, ANTI, or ANTI-V tasks (Ishigami & Klein, 2010; MacLeod et al., 2010; Roca et al., 2018). Therefore, it might be reasonable to think that those performance scores, which are more reliable and stable across experimental sessions, are the ones that correlate with white matter microstructural connectivity. In this vein, it has been proven that white matter connectivity is strongly related to long term stable changes, as maturation (Lebel, Walker, Leemans, Phillips, & Beaulieu, 2008), or the structural damage linked with diseases as stroke, schizophrenia, or multiple sclerosis (Le Bihan et al., 2001).

However, this reasoning does not seem to fit well with the strong and independent correlation observed between the HMOA indices of both the right DLPFC and the splenium of the CC, and phasic alertness, which is interpreted as a measure of attentional state rather than a stable trait (MacLeod et al., 2010). To account for this latter pattern of findings, nevertheless, we might consider that: (a) although phasic alertness refers to a short term process that shows moderate-to-low reliability in the present study and also in previous studies with the ANT (MacLeod et al., 2010) or ANTI-V (Roca et al., 2018), the phasic alertness score (both for RT and errors) demonstrated both a considerable stability when it was assessed with the ANTI task across 10 consecutive sessions, and a moderate-to-high split-half reliability (i.e., .70 for the errors score) when it was computed considering the data of these 10 sessions (Ishigami & Klein, 2010); (b) the right DLPFC and the splenium of the CC effectively connects brain regions of the alerting network circuit, i.e., brain stem regions as the locus coeruleus along with prefrontal and parietal cortices (S. E. Petersen & Posner, 2012; Posner, 2012b). Notwithstanding, although these findings might be quite relevant for disentangling the underlying white matter connectivity of the alerting network, further research supporting this evidence is imperatively necessary.

Critically, we did not replicate previous findings supporting relevant associations between: (a) the orienting functioning and the splenium of the CC (Niogi et al., 2010) and/or the SLF III (Thiebaut de Schotten et al., 2011); (b) executive control processes and the left DLPFC (Chiang et al., 2015); and (c) the EV component and the left cingulate fasciculus

(Takahashi et al., 2010) and/or the right DLPFC (Chiang et al., 2015). As above-mentioned, Bayesian analyses demonstrated that evidence accumulated was weak or anecdotal to support the existence of the correlations between the RT score of orienting and the SLF III, and the left DLPFC and the RT score of executive control. Furthermore, the correlations between the splenium of the CC and RT score of orienting, and sensitivity with either the right DLPFC or the right cingulate, were observed as inconsistent evidence to support either the H_0 or the H_1. Thus, again, we consider that much further evidence is necessary in future research to determine the potential existence of these correlations.

To further account for this set of non-replicated findings above-mentioned, we might consider some differences between the current study and the previous ones. For instance, Niogi et al. (2010) assessed the classic attentional components with the ANT, which presents a different cueing paradigm for measuring phasic alertness and orienting than the ANTI (Callejas et al., 2004) and ANTI-V (Roca et al., 2011). In particular, whereas in the ANT task the orienting cue is 100% predictive of target location, in the ANTI task the cue is not completely predictive. Moreover, it might be probable that some previous findings obtained by the FA index, as those reported by Niogi et al. (2010) and Chiang et al. (2015), would not be successfully replicated by using the most sensitive HMOA index. Interestingly, note also that participants from the Chiang et al. (2015) study were young participants between 7 and 18 years old, and so, it might be highly probable that some differences with the findings obtained there would be linked to maturation factors (Lebel et al., 2008). Nevertheless, as above-mentioned, we consider that further research is critically necessary to support the discussions provided here, and most importantly, to achieve a consensus regarding the structural connectivity underlying human attentional networks.

Finally, although we observed a relevant correlation between the right and left SLF I connectivity and the overall mean RT for the EV task, the SDT metrics – which are indeed the most descriptive indices of EV as the ability to detect infrequent critical signals over long time periods –, showed no correlations with white matter tracts connectivity. To account for this inconsistent finding, it might be relevant to take into account some limitations of the ANTI-V task on the assessment of EV. Although the SDT scores computed here and in previous research (Roca et al., 2018) showed a high reliability, the EV task is indeed a signal detection task quite difficult to perform. Thus, the hits rate observed here (i.e., 46% overall across sessions) is similar to the one observed in previous studies with the ANTI-V, wherein it was found between 45% and 60% as maximum (Marotta et al., 2015; Morales et al., 2015; Roca et al., 2011, 2012; Roca, Crundall, et al., 2013; Roca, Lupiáñez, et al., 2013). Furthermore, and most importantly, the above-cited studies with the ANTI-V have not reported the decrement of performance across time on task, i.e., the typical phenomenon usually observed in vigilance tasks (Hancock, 2017). In this vein, when either the RT or SDT metrics of the current study are analyzed comparing the performance across time on task (i.e., by experimental blocks), the repeated-measures ANOVAs show indeed no significant shift across blocks (all *F*s < 1.16, *p*s > .330).

Therefore, future studies aiming at examining the structural connectivity underlying the human attentional networks and vigilance processes, might consider to use a newest version of the ANT: the ANT for Interactions and Vigilance – executive and arousal components (ANTI-Vea; Luna, Marino, Roca, & Lupiáñez, 2018). This new task is suitable to assess the independency and interactions of the classic attentional components as in the ANTI (Callejas et al., 2004), but (at the same time), it provides an independent and direct measure of two vigilance components: (a) the EV, as the ability to detect infrequent critical signals; and (b) the arousal vigilance (AV), a component usually assessed in the Psychomotor Vigilance Test (PVT; Lim & Dinges, 2008) as the capacity to sustain across time on task a fast reaction to stimuli from environment without implementing much control (Luna et al., 2018). Note that, importantly, the ANTI-Vea solves the above-mentioned issues of the ANTI-V task: (a) the EV task is easier to perform, as observed in the overall hits rate of ~75%; and (b) the task is suitable to observe the decrement across time on task for both the EV and AV components (Luna et al., 2018). Thus, it might be expected that a behavioral task suitable to assess the vigilance decrement phenomenon, which is the behavioral pattern by definition of vigilance (Hancock, 2017; Mackworth, 1948), could be indeed more sensitive to reflect potential implications of white matter tracts connectivity underlying this behavior.

Conclusions

To conclude, while the present research aimed at examining and dissociating the white matter connectivity underlying the human attentional networks, we only found consistent evidence – supported by both NHST and Bayesian approaches – concerning the right DLPFC and the splenium of the CC as associated with the alerting network. Regarding the role of the right SLF III in the orienting network, and the left DLPFC tracts in the executive control network, the evidence collected in the present study seems to be weak for supporting these pair of correlations, and no further relevant correlations were observed for orienting and executive control. In addition, the SDT scores of EV – which are the most informative indices regarding the ability to detect infrequent signals in long time periods –, were not associated in the present study with the right cingulate and right DLPFC, at difference with findings reported in previous studies. However, note that interestingly, white matter connectivity seems to support performance reliability : whereas the left cingulate seems to be associated with the mean overall RT of attentional networks performance, both left and right SLF I were associated with the overall RT of EV performance. Finally, while the evidence collected in the present study seems to support the absence of a large pattern of correlations between HMOA and attentional/vigilance performance, there was another set of correlations in which the evidence seems to be inconsistent or weak to confirm the findings. Therefore, to better understand the controversial relationship between attentional processes and white matter connectivity, and to disentangle the inconsistent findings observed in the present study, we consider that much further evidence is critically necessary.

Chapter VIII

General Discussion

The present dissertation aimed at providing a theoretical framework in which the EV and AV components of vigilance can be considered as two independent mechanisms of the attentional networks system (Oken et al., 2006; S. E. Petersen & Posner, 2012; Posner, 2008; Posner & Dehaene, 1994; Posner & Petersen, 1990) and examining whether this dissociation can be empirically supported by behavioral and neural data. To do so, we carried out five experimental series wherein we have consistently addressed both a theoretical and empirical dissociation between these two vigilance components. In particular, along Experimental Series 1 to 3, we analyzed the behavioral patterns of the EV and AV decrement when assessed in the context of the classic attentional networks functions. Note that, to this end, another important goal of the present work was to develop a behavioral task (i.e., the ANTI-Vea) suitable to assess, within a single session, both vigilance components along with the independence and interactions of phasic alertness, orienting, and executive control. Furthermore, in order to provide a useful tool to the scientific community, we aimed at developing a friendly and free website to measure attentional and vigilance components and the functioning of the three attentional networks, which constituted another important goal of the present dissertation. Moreover, across Experimental Series 4 and 5, we aimed at further analyzing the neural mechanisms that modulates the human attentional networks, with a particular interest in dissociating the brain circuits underlying the functioning of vigilance components. Whereas a deeper discussion of the findings of the present dissertation has been specifically presented in each experimental series, in the following sections we will discuss the main contributions of the present work to the theoretical and empirical dissociation of the EV and AV components as two independent mechanisms of the attentional networks system.

The ANTI-Vea task

One of the main contributions of the present dissertation was to develop a behavioral task that is suitable to assess, within a single session, the independence and interactions of the classic attentional components along with the EV and AV decrement across time on task. In particular, we expected the ANTI-Vea would be a task: (a) as effective as the ANTI to assess the main effects and interactions of the classic attentional components (Callejas et al., 2005, 2004); (b) more sensitive than the ANTI-V to assess the EV component (Roca et al., 2011); and (c) as suitable as the PVT to assess the AV component (Basner & Dinges, 2011; Lim & Dinges, 2008).

Measuring phasic alertness, orienting, and executive control with the ANTI-Vea

Regarding the classic attentional components, the results obtained across Experimental Series 1 to 4 consistently demonstrate that the main effects of phasic alertness, attentional orienting, and executive control, are successfully assessed as in the ANTI task (Callejas et al., 2004) even when the EV and AV component are measured at the same time. In short: (a) the typical effect of warning signal was observed for phasic alertness as faster and more accurate responses in the tone than in the no tone condition (Posner, 2008); (b) for attentional orienting, the facilitation effect of cueing was observed as expected for RT, providing a measure of both benefits (RT valid < no cue) and costs (RT invalid > no cue) (Callejas et al., 2004; Posner, 2014); and (c) the interference effect of distractors for executive control was observed as it is usually found with the flanker task, i.e., responses were faster and more accurate when distractors are congruent with the target, than when they are incongruent (Eriksen & Eriksen, 1974; Funes et al., 2010). In addition, the typical modulations among the classic attentional components usually observed with the ANTI task were also replicated by using the ANTI-Vea (note that a detailed description of these interactions has been presented in Experimental Series

1 and 3), which provides further evidence for the effectiveness of the ANTI-Vea to assess both the main effects and interactions of the classic attentional components (Callejas et al., 2005, 2004; S. E. Petersen & Posner, 2012; Posner & Petersen, 1990).

Furthermore, the independence between the classic attentional networks functions was analyzed by correlating the attentional scores – i.e., computed by subtracting average data in specific conditions – of phasic alertness (i.e., no tone minus tone, only in the no cue condition), orienting (i.e., invalid minus valid), and executive control (i.e., incongruent minus congruent) (Callejas et al., 2004; J Fan et al., 2002). In the same vein with the predictions stated by the attentional networks model (S. E. Petersen & Posner, 2012; Posner & Dehaene, 1994; Posner & Petersen, 1990), phasic alertness, orienting, and executive control showed a strong independence among them (a detailed description of these results have been addressed in Experimental Series 3). Importantly, it must be noticed that the scores of the three classic attentional components showed a similar size among them (i.e., ~45 ms, see Experimental Series 3) when assessed with the ANTI-Vea. We consider this finding as an additional advantage of the ANTI-Vea when measuring the classic attentional components in comparison with former versions of the task, wherein the executive control score was observed at least twice the size of the phasic alertness and orienting scores (Callejas et al., 2004; J Fan et al., 2002; Roca et al., 2011). Note that the fact that the executive control score was much larger than the other components in previous versions of the ANT task might have an influence in the general finding that it is precisely the executive control score the one more usually modulated by the different manipulations (Medina & Barraza, 2019; Perrier et al., 2015; Rodríguez-Bailón, Triviño, & Lupiáñez, 2012). Therefore, providing a similar size score for each attentional function might be an interesting property of the ANTI-Vea task newly developed in the present dissertation.

Furthermore, to specifically account for the reduction on the interference effect (i.e., the executive control score) observed with the ANTI-Vea, we decided to conduct a separate study (not presented as part of the present dissertation) to properly address this issue (Luna, Telga, et al., 2019). Note that this study was motivated by a set of serendipitous results observed in the development of the ANTI-Vea, task reported in Experimental Series 1, wherein we observed a significantly smaller interference effect in the vertical version of the ANTI-V/ANTI-Vea than in the horizontal version of the task (Luna et al., 2018). Thus, we conducted a new experimental series with preregistered hypotheses (https://osf.io/h4tk7/) in which we predicted that the distractors interference for executive control functioning might be considerably reduced or increased depending in particular of the attentional set maintained in working memory when performing dual tasking. Indeed, after analyzing data collected from five different experiments, we concluded that, in comparison with the interference effect observed when just performing a flanker task (i.e., ~55 ms and ~3.5% of errors), the concurrent working memory load of dual tasking effectively: (a) benefits executive control by reducing the distractors interference (i.e., ~33 ms and ~-0.5% of errors) when the secondary task helps to perceptually segregate the target from distractors (i.e., by detecting an infrequent vertical displacement of the target, as in the ANTI-Vea); but (b) impairs executive control by increasing the distractors interference (i.e., ~87 ms and ~10.0% errors) when the secondary task boosts the perceptual grouping of the target and distractors (i.e., by detecting an infrequent horizontal displacement of the target, as in the previous ANTI-V developed by Roca et al., 2011) (Luna, Telga, et al., 2019).

The ANTI-Vea improves the assessment of the EV decrement

In addition to our expectation for the ANTI-Vea to be a suitable task for measuring the classic attentional components, one of the main challenges with this new task was to solve some issues previously observed with the EV measure of the ANTI-V (Roca et al., 2011). In particular: (a) the EV task of the ANTI-V seems to be quite difficult to be performed, as demonstrated by the low hits rate (i.e., between 45% and 60%) observed in former studies in healthy adults (Roca et al., 2011, 2012; Roca, Crundall, et al., 2013; Roca, Lupiáñez, et al., 2013); (b) critically, the vigilance decrement phenomenon was not reported across blocks of trials in the above-cited studies with the ANTI-V, and the reduction of EV across time was demonstrated only after ~26 hours of total sleep deprivation (Roca et al., 2012); and (c) the ANTI-V has shown some problems when measuring EV in healthy older adults (i.e., a ~44% of the sample had to be excluded in a study due to an extreme low performance; Moratal, Huertas Olmedo, & Lupiáñez, 2015). Note that we have replicated some of these issues in Experimental Series 5, wherein we assessed EV with the ANTI-V task, and we observed both a hits overall of ~46% and no decrement across time on task.

Thus, by taking all the above-mentioned considerations into account, in Experimental Series 1, we proposed a modified version of the infrequent critical signal for the EV task, which we expected to significantly improve the hits rate in comparison with the performance usually observed with the ANTI-V (Roca et al., 2011). In particular, we hypothesized that a vertical displacement of the target, orthogonal to the horizontal grouping dimension of the distractors, could be perceptually more salient and therefore easier to be detected, than the horizontal displacement of the target used in the ANTI-V (Roca et al., 2011). As demonstrated across Experimental Series 1 to 3, but specifically in the Experimental Series 3 – wherein a large sample size was assessed with the standard ANTI-Vea – the overall hits rate increases notably (~75%) when the infrequent signal is a vertical displacement of the target, in comparison with the performance observed when detecting the horizontal displacement of the ANTI-V (Roca et al., 2011).

Furthermore, we also expected the ANTI-Vea to be a task suitable to solve some issues recently objected (see below for a detailed description) to the traditional single and monotonous vigilance tasks, like the SART (Robertson et al., 1997), the CPT (Conners, 2000), or the MCT (Mackworth, 1948), when attempting to assess the vigilance decrement phenomenon (Thomson et al., 2016). Note that, over several decades, the EV decrement has been widely-accepted as a progressive loss in the sensitivity to discriminate infrequent but critical signals from the remaining noise events (See et al., 1995; Warm et al., 2008). However, recently, Thomson et al. (2016) observed that single vigilance tasks are indeed very easy to perform by participants, and so in general it is found a ceiling effect on the hits along with a floor effect in the FA rate. Importantly, note that if the EV decrement corresponded to a considerable shift in the response bias rather than to a loss in sensitivity, then it would be necessary that the typical drop in the hits observed across time on task be accompanied with a similar drop in the FA rate. However, this is something highly unlikely to occur if FAs are already at the floor at the beginning at the task (Thomson et al., 2016). Moreover, Thomson et al. (2016) strongly objected the use of parametric indices of SDT (i.e., d′ for sensitivity and β for response bias) to analyze the EV decrement when the hits are at the ceiling and FAs are at the floor, and so they proposed that the EV decrement should be better analyzed with non-parametric indices of sensitivity (i.e., A′) and response bias (i.e., B″) (for a detailed discussion on this issue, see Stanislaw & Todorov, 1999; Wixted, 2019). Therefore, taking all the above-mentioned issues into account, Thomson et al. (2016) conducted an empirical demonstration wherein it was proved that, indeed, if FAs are not at floor then the EV decrement is best interpreted as a progressive increment in the response bias rather than as a loss in sensitivity.

Following the theoretical and empirical demonstration conducted by Thomson et al. (2016), in Experimental Series 2 we proposed a novel version of the ANTI-Vea which included some lure trials (i.e., as similar as the experimental paradigm developed by Thomson et al., 2016) that should increase notably the FA rate in comparison with the standard ANTI-Vea developed in Experimental Series 1. Although we succeed in observing a significant increment in the FA rate with the lure version of the ANTI-Vea, the EV decrement was better observed as a linear increment in the response bias with the standard than with the lure version of the task. Nevertheless, and critically, to avoid a floor effect in the FA rate with the standard ANTI-Vea, we proposed in Experimental Series 2 a novel analytical method to compute the FA rate only considering events in which substantial noise is present (i.e., ANTI trials in which the central target is at least 3 pixels displaced from one of the surrounding arrows) in which it would be more likely to observe a FA (i.e., in line with what is expected in the lure trials).

Note that, importantly, although the hits rate observed with the ANTI-Vea is higher than the one usually observed with the ANTI-V, it is nevertheless far to be close of the ceiling effect usually observed with the traditional single vigilance tasks (Thomson et al., 2016). In particular, the hits rate observed for the single EV tasks of Experimental Series 2 (i.e., ~88%) is quite higher than the one observed in the standard ANTI-Vea in Experimental Series 3 (i.e., ~75%). Furthermore, it must be noticed that the sensitivity-loss effect was specifically observed with the single EV tasks administered in Experimental Series 2 (even when computing FAs with the analytical method proposed by Thomson et al., 2016), which are indeed very similar to the traditional single and monotonous vigilance tasks like the MCT (Mackworth, 1948) or the SART (Robertson et al., 1997). However, as demonstrated in Experimental Series 3, wherein the EV decrement was assessed in a large sample size with the ANTI-Vea, the sensitivity-loss effect seems to be dependent on the FA rate at the beginning of the task: whereas a significant decrement in the sensitivity was observed when FAs were equal or lower than 5% in the first experimental block, no decrement in the sensitivity was found when FAs were higher than 5% in the first block.

Therefore, and to summarize the improvements observed when measuring the EV component with the ANTI-Vea task, we can conclude that: (a) the vertical displacement of the target is indeed easier to be detected as the infrequent critical signal, and so the hits rate is higher than the one usually found with the ANTI-V (Roca et al., 2011), but importantly, detection is not at ceiling as commonly observed with traditional single vigilance tasks; (b) the novel analytical method used to compute FAs is effective to avoid a floor effect (Thomson et al., 2016); (c) the sensitivity-loss across time on task is more likely to be observed with the traditional single EV tasks (See et al., 1995), and most importantly, it seems to be dependent upon whether the FA rate is at floor in the first period of the task (Thomson et al., 2016); and (d) critically, if FAs are not at the floor, then the EV decrement is best interpreted as a considerable increment in the response bias towards a more conservative criterion (Claypoole et al., 2018; Thomson et al., 2016). Finally, it is important to note that, while the ANTI-Vea has proved to be adequate for measuring attentional and vigilance components in 8 and 9 years children (Huertas et al., 2019), in a future study that will be conducted in our lab we also expect the ANTI-Vea can be successfully completed by healthy older adults, at difference with the ANTI-V which showed some issues when administered to older adults (Moratal et al., 2015).

The ANTI-Vea is suitable to assess the AV decrement

As above-mentioned, to examine an empirical dissociation between the EV and AV components, we considered imperatively necessary to develop a task suitable to assess both vigilance components at the same time. To do so, a second main challenge when developing the ANTI-Vea was to incorporate a direct AV measure that could be sensitive to assess the decrement of this component across time on task. Thus, in Experimental Series 1 we proposed to add a small proportion of trials to the design of the ANTI-V, in which participants performed a task similar to the PVT (Lim & Dinges, 2008), i.e., to stop a millisecond down counter at random intervals of time by pressing as fast as possible any available key. Importantly, note that the PVT is usually administered every one or two hours during a specific period of time to assess the effects of total or partial sleep deprivation over AV (Basner & Dinges, 2011; Lim & Dinges, 2008). Thus, with the PVT, the AV decrement is generally reported as the impairment of performance across the total time of evaluation (Basner et al., 2011; Lamond et al., 2005; Loh et al., 2004).

However, along Experimental Series 1 to 4, we have consistently demonstrated that with the ANTI-Vea, the AV decrement can be successfully assessed within a single session of ~33 minutes. In particular, the AV decrement was found as a progressive increment in three of the most sensitive measures generally used with the PVT, i.e., the mean RT, the RT variability, and the percentage of lapses (Basner & Dinges, 2011). Interestingly, it should be noted that in the PVT, lapses are commonly considered as the responses equal or slower than 500 ms (Basner & Dinges, 2011). However, note that whereas with the PVT the mean RT is usually observed between ~250 and ~270 ms (Basner & Dinges, 2011; Blatter et al., 2006; Drummond et al., 2005; Lee et al., 2010; Lim & Dinges, 2008; Loh et al., 2004), with the ANTI-Vea the mean RT of AV was found ~200 ms higher (i.e., ~487 ms in the standard task of Experimental Series 3). It could be possible that the slower overall RT observed for AV would be due to the fact that, at difference with the PVT, in the ANTI-Vea participants have to maintain in working memory a large set of instructions to perform three different tasks simultaneously, while receiving further stimuli as warning signal, visual cue, and a set of target and distractors. Therefore, taking the above-mentioned issues into account, we decided to compute the lapses in the ANTI-Vea as the responses equal or higher than 600 ms (a more detailed discussion has been presented in Experimental Series 1), which demonstrated to be a sensitive threshold for measuring the AV decrement as an increment of the percentage of lapses across time on task.

The ANTI-Vea is a reliable method that can be administered online

Although in Experimental Series 1 and 2 we consistently found that the ANTI-Vea is a suitable task to assess the main effects and interactions of the classic attentional components along with the EV and AV decrement, we decided to perform the Experimental Series 3 wherein we collected data from a large sample size to address two specific goals: (a) to analyze the split-half reliability of the attentional and vigilance scores computed with the ANTI-Vea (Ishigami & Klein, 2010; MacLeod et al., 2010; Roca et al., 2011); and (b) to examine whether the ANTI-Vea is suitable to be administered through an online website outside the lab (Claypoole et al., 2018). Importantly, note that the split-half reliability scores computed with the standard ANTI-Vea (i.e., performed in the typical lab conditions) were indeed very similar to the ones computed with the online ANTI-Vea (i.e., completed in an online session outside the lab). Moreover, the split-half reliability observed with the ANTI-Vea replicated some findings previously observed with the ANTI and the ANTI-V tasks (MacLeod et al., 2010; Roca et al., 2018) Thus, for the ANTI scores computed with the ANTI-Vea, the highest reliability was found for the overall RT (i.e., .99) and percentage of errors (i.e., ~.90), whereas executive control showed a moderate to high reliability (i.e., ~.67 for the RT score), and in the same vein with previous findings, the lowest reliability (i.e., <.40) was observed for the scores of both phasic alertness and orienting. Furthermore, and most importantly, both the EV and AV showed a relative high reliability (i.e., between .71 and .99, considering all the EV and AV scores), thus providing additional evidence for measuring the vigilance components with the ANTI-Vea, either in the typical lab conditions or in an online session completed outside the lab.

Importantly, regarding the feasibility of measuring online outside the lab, it should be noted that although only a few studies have administered online vigilance tasks to assess in particular the EV component to date (Fortenbaugh et al., 2015; Ralph et al., 2015; Sadeh et al., 2011; Thomson et al., 2016), in the present dissertation we provide novel and consistent evidence concerning that the online ANTI-Vea is as effective as the standard ANTI-Vea to assess: (a) both the EV and AV decrement across time on task (Claypoole et al., 2018), and (b) the main effects and interactions of the classic attentional components. Therefore, we expect that the online ANTI-Vea might be a useful version for researchers interested in measuring attentional and vigilance components with a reliable method that is, indeed, publicly and freely available in an open website (https://www.ugr.es/~neurocog/Sitio_web/ANTI/).

Indeed, we are currently working on the design of the above-mentioned website to make this tool much easier to be used for researchers interested in measuring attentional and/or vigilance components in applied contexts. For instance, in the website a wide set of attentional and/or vigilance tasks to be administered is available, e.g., the ANTI-Vea, the ANTI-V, the ANTI, a single EV task, a single AV task, or a dual EV-AV task as the one used in Experimental Series 2. Furthermore, it could be possible that some researchers would want to slightly modify the experimental procedure of a particular task to make it more suitable for a specific population (e.g., clinical patients, children, or older adults). Therefore, an options panel is available wherein some settings can be predefined prior to the task administration, e.g., to increase the displacement of the target to facilitate its detection, to reduce the number of experimental blocks to make the task shorter tin he total time of duration, and/or to increase the duration of the target presentation. Furthermore, another website (https://www.ugr.es/~neurocog/Sitio_web/AntiResults.html is available for the researchers to download the raw data, either collected with a single participant or an entire sample.

The task is available in six different languages (Spanish, English, German, Italian, French and Polish) to facilitate cross-language data collection, and international many-labs collaborations. Indeed, the task has been already used in Spain to study the effect of musical training (Román-Caballero, personal communication), and the effect of relative age (comparison of older vs. younger players within a category) of footballers (Huertas et al., 2019) on attentional performance and vigilance. It is also being used in Poland to investigate the effect of lack of control suffered by long duration unemployed people on vigilance performance (Bukowski, personal communication), and the NEDEA clinic in Granada has started to use it to online evaluate attentional deficit hyperactivity disorder (ADHD) children before and after treatment. Lastly, the online ANTI-Vea is also being used to test the effects of different stress reduction methods on attentional and vigilance components functioning (Funes, personal communication).

The neural mechanisms underlying attentional and vigilance components

Whereas across Experimental Series 1 to 3 we specifically examined the behavioral patterns of the attentional and vigilance components measured with the ANTI-Vea, in the Experimental Series 4 and 5 we aimed at further analyzing the neural mechanisms underlying the attentional networks system (S. E. Petersen & Posner, 2012; Posner, 2012b; Posner et al., 2006). Thus, in short, while in Experimental Series 4 we found a critical role of the right fronto-parietal network for phasic alertness and EV, in Experimental Series 5 we were able to only disentangle the white matter connectivity associated with phasic alertness and overall RT scores of the attentional and the EV performance. In the following sections, we will more deeply discuss the main contributions of the present dissertation to the examination of the neural mechanisms underlying the attentional networks system.

The brain activity associated with the alerting network

Although in the last years there has been a growing interest in the use of tDCS as a potential tool to modulate attentional and/or vigilance performance, the evidence reported to date is both scarce and ambiguous at best (Coffman et al., 2014; Dedoncker et al., 2016; Reteig et al., 2017). Thus, the Experimental Series 4 was conducted with the specific aim of more deeply examining the effects of anodal tDCS over the functioning of the attentional and/or vigilance components, by stimulating two core regions of the attentional networks system: the right PPC or the right DLPFC (S. E. Petersen & Posner, 2012; Posner, 2012b; Posner et al., 2006). To do so, we used a HD-tDCS approach, which has been demonstrated to deliver stimulation with more precision over the region of interest than conventional tDCS protocols (Datta et al., 2009; Kuo et al., 2013). Furthermore, to examine whether anodal stimulation is an effective tool to modulate the vigilance decrement phenomenon, we administered HD-tDCS at the same time (i.e., online) that participants completed the ANTI-Vea task, unlike previous attentional or vigilance studies wherein tDCS was delivered offline (i.e., before performing the behavioral task) (Coffman et al., 2012; Jacoby & Lavidor, 2018; Lo et al., 2019; McIntire et al., 2017; Roy et al., 2015).

In short, the main findings of Experimental Series 4 are that online anodal HD-tDCS over the right PPC and DLPFC, independently on the brain region: (a) mitigates the EV decrement across time on task, but does not modulates the AV decrement; and (b) improves the effectiveness of responses under a phasic alertness state, but does not modulates attentional orienting and executive control functioning. Note that the effects of anodal HD-tDCS over the right PPC and DLPFC are specifically related to some of the cognitive components modulated by the alerting network, which is indeed a brain circuit that comprises brain stem regions as the locus coeruleus along with right parietal and prefrontal cortices (S. E. Petersen & Posner, 2012; Posner, 2008, 2012b). However, and most importantly, as observed in the Experimental Series 4, it seems that these neural mechanisms that modulate EV (and the effectiveness of responses under phasic alertness) are independent from the neural mechanisms that modulate the AV performance across time on task.

In addition, in Experimental Series 4 we have also observed that anodal HD-tDCS reduces the increment of alpha power (i.e., 7.5 to 12.5 Hz) across time on task in the right parietal cortex in particular. Note that the increment of alpha power has been consistently linked to states of reduced alertness, as sleep and the vigilance decrement phenomenon (Boksem et al., 2005; Clayton et al., 2015). However, as demonstrated in Experimental Series 4, the modulation of anodal HD-tDCS over alpha power seems to be an independent mechanism of the EV and AV decrement across time on task. Nevertheless, it has been recently found that if alpha power is stabilized (i.e., at 10 Hz) across time by stimulating the occipitoparietal cortex with transcranial alternating current stimulation (tACS; a suitable stimulation technique to modulate specifically a band of electrical cortical rhythms), then the EV decrement is mitigated in both the hits and the RT of responses (Clayton, Yeung, & Cohen Kadosh, 2019). Therefore, to further determine the role of alpha power in the vigilance decrement phenomenon, in future research it would be interesting to examine if alpha tACS exclusively modulates the EV decrement but not the AV one.

Indeed, note that whereas alpha increment was previously related to the EV decrement (Boksem et al., 2005; Clayton et al., 2019), the decrement on the PVT during a night of sleep deprivation was associated with a progressive increment on delta (1-4 Hz) and theta (4-8 Hz) power, but not in the alpha band (Hoedlmoser et al., 2011). Thus, to better disentangle the role of the cortical oscillatory rhythms on the EV and AV decrement, we are currently conducting a new study wherein participants complete the ANTI-Vea task while EEG signal is registered in all the experimental blocks (i.e., at difference with Experimental Series 4, in which EEG signal was recorded only at baseline and post-stimulation).

The structural connectivity underlying attentional networks

Importantly, whereas there has been a notable interest in the study of the brain activity associated with the attentional networks system, the evidence reported concerning the structural brain circuits underlying attentional networks is, at least, scarce and controversial so far (S. E. Petersen & Posner, 2012; Posner, 2012b; Posner et al., 2006). Thus, the Experimental Series 5 aimed at providing further evidence regarding the white matter connectivity underlying the functioning of the attentional networks and vigilance. Note that, in addition, we aimed at overcoming some issues observed when analyzing the connectivity of white matter tracts. Therefore, in particular, we reconstructed DWI data with the spherical deconvolution approach (Alexander, 2005; Tournier et al., 2004) and analyzed the connectivity of fiber tracts with the HMOA index (Dell'Acqua et al., 2013), two methods that have proven to be more sensitive when examining the white matter properties of brain regions wherein multiple crossing fibers converge (as, for instance, the SLF; see Thiebaut de Schotten et al., 2011).

Thus, in summary, one of the main findings of Experimental Series 5 is that the connectivity of the right dorsolateral prefrontal caudate tracts and the splenium of the corpus callosum seem to underlie the effectiveness of responses under a phasic alertness state. However, none relevant correlations were observed between white matter connectivity and the performance of attentional orienting or executive control. In addition, it seems that white matter connectivity is better associated with those performance scores which are more reliable and stable across experimental sessions. In this vein, we found that (a) the higher the connectivity of the left cingulate fasciculus, the faster the overall responses in attentional networks performance; and (b) the higher the connectivity in both left and right SLF I, the faster the responses for the correct detection of infrequent signals in EV performance. Lastly, there were no relevant associations between white matter tracts and the SDT metrics computed for EV. Nevertheless, importantly, it should be noted that whereas it seems adequate that the white matter tracts associated with phasic alertness indeed connect brain regions implicated in the alerting network, as brain stem nuclei and the right prefrontal and parietal cortices (S. E. Petersen & Posner, 2012; Posner, 2008, 2012b; Posner & Petersen, 1990), we consider that further research is necessary to better understand the implications of the white matter tracts connectivity associated with overall RT performance in the attentional networks and EV.

Finally, it is important to highlight that whereas the above-mentioned findings were found both as significant results to reject the null hypothesis by Pearson correlations, and also as positive or strong evidence for the alternative hypothesis by Bayesian correlations, a critical finding of Experimental Series 5 derived from Bayesian analyses is that much evidence is still necessary to better analyze some weak or inconsistent correlations observed (e.g., the negative correlation found between right cingulate fasciculus and executive control). In addition, note that a considerable limitation of the Experimental Series 5 is that attentional components and EV were assessed with the ANTI-V task, which has shown several issues at measuring the EV component (Roca et al., 2011). Therefore, with the aim to overcome this limitation observed in Experimental Series 5, and also to accumulate much evidence regarding the white matter connectivity underlying attentional and vigilance components, we are currently working on a study with a larger sample size (N = 60) in which DWI data will be correlated with the attentional and vigilance components scores of the ANTI-Vea task.

Are EV and AV two dissociated components?

In the present dissertation, we have consistently observed that the EV and AV decrement can be assessed independently within a single session. In particular, whereas the EV decrement corresponds to a decline in the ability to detect infrequent critical signals, the AV decrement is best interpreted as a progressive slowness for reacting to stimuli from environment without implementing much control over responses. Whereas some relevant findings concerning a potential dissociation between EV and AV have been already discussed, we would like to conclude the present dissertation by introducing: (a) a theoretical analysis of previous literature wherein vigilance is conceived as a multiple concept; and (b) a set of novel and critical evidence that seems to support the hypothesis that EV and AV can be indeed considered as two dissociated components.

A theoretical distinction between EV and AV

A first theoretical discussion of vigilance as a multiple concept arises from the fact that, to date, a considerable controversy in the cognitive and brain research literature is observed when using the term vigilance. Thus, on the one hand, there seems to be a wide agreement to use vigilance as a concept to denominate the ability of the cognitive system for sustaining an optimal level of attention over long time periods (Mackworth, 1948; Posner & Dehaene, 1994; Posner & Petersen, 1990; Thomson, Besner, et al., 2015; Warm et al., 2008). However, on the other hand, the term vigilance has been also used in a broad sense for referring to different processes modulated by the alerting network, in particular: (a) the shifts of the arousal levels during the sleep-wake cycle, which are not associated with a particular behavioral responsiveness, (b) a hypervigilance state necessary for coping with, preventing or anticipating potential dangers or threats, and (c) the ability for sustaining attention over long periods of time within an experimental task (Oken et al., 2006).

Furthermore, at the neural level, some theoretical reviews aimed at dissociating the concept of vigilance from terms as intrinsic alertness and the arousal levels of attention, by analyzing the mechanisms modulated by the alerting network (Langner & Eickhoff, 2013; Sarter et al., 2001; Shallice, Stuss, Alexander, Picton, & Derkzen, 2008; Sturm & Willmes, 2001). For instance, Sarter et al. (2001) have proposed that vigilance may be indeed conceived as a distinct mechanism from the arousal components of attention. The authors described vigilance as a behavioral function to detect unusual targets that is supported by a top-down functioning of the cholinergic neural system. In contrast, the arousal component of attention may not involve a specific behavioral responsiveness, but could rather be necessary for the development of vigilance across time by the bottom-up innervations of the noradrenergic system. A similar distinction has been examined by Langner & Eickhoff (2013), who proposed that whereas vigilance might be understood as the maintenance of attention for detecting or discriminating stimuli in monotonous and intellectually unchallenging tasks, the concept of arousal or sustained attention would refer to a mechanism developed by several neuromodulatory systems for regulating a general level of excitability that, indeed, might support the functioning of vigilance.

In addition, another controversial use of the concept of vigilance is observed in the behavioral tasks that examine the decrement of performance across time on task. Thus, as it was discussed systematically along the present dissertation, in tasks such as the MCT (Mackworth, 1948), the SART (Robertson et al., 1997), or the CPT (Conners, 2000), vigilance is assessed as the ability to sustain attention over long time periods to detect rare but critical signals by executing a specific response, a cognitive component that we have denominated here as EV. Importantly, this conception of EV seems to be closer to the behavioral mechanisms of vigilance described by Sarter et al. (2001) and Langner & Eickhoff (2013). In contrast, the tasks such as the PVT (Lim & Dinges, 2008) assess vigilance as the capacity to maintain a fast reaction to stimuli without implementing much control over responses, which is the cognitive component that we have denominated AV. Note that as AV is usually impaired under conditions of partial or total sleep deprivation (Basner & Dinges, 2011; Lim & Dinges, 2008), this component might be conceived as the behavioral responsiveness of the arousal levels of attention (Langner & Eickhoff, 2013; Sarter et al., 2001), or the shifts of arousal during the sleep wake cycle (Oken et al., 2006).

The independence between EV, AV, and the classic attentional components

From an empirical analysis, a further examination of the dissociation between EV and AV was addressed in Experimental Series 3, in which we conducted bivariate correlations between attentional and vigilance components with a large amount of evidence collected. Critically, we observed a relative large independency between the SDT metrics of EV (i.e., which are, indeed, the most sensitive scores to describe EV as the ability for detecting infrequent signals) and the RT measures computed for AV, a set of findings that strongly support an empirical dissociation between EV and AV. In particular, we only observed a weak (i.e., between .15 and .22) although significant pair of negative correlations between both the hits and the sensitivity of EV with the RT variability of AV, and also some moderate correlations (i.e., between .30 and .50) between the RT scores of EV and AV. Thus, it might be possible that, in the same vein to the theoretical models proposed by Sarter et al. (2001) and Langner & Eickhoff (2013), although EV and AV can be indeed considered as separated mechanisms, the generals levels of excitability regulated by AV could be underlying the behavioral responsiveness of EV to correctly detect infrequent critical signals in an extended period of time. However, further research linking neuroimaging and behavioral data may contribute to better examine a potential modulation between the behavioral and neural mechanisms of EV and AV (Posner, 2012b; Posner et al., 2006).

In addition, note that EV and AV seem to be associated with different mechanisms of the classic attentional networks components. On the one hand, the ability of EV for detecting infrequent critical signals was particularly associated with the attentional mechanisms that modulate the accuracy of responses (e.g., the higher the errors in the ANTI task, the higher the FAs in the EV task). Moreover, and interestingly, a moderate but significant negative correlation (.-35) was observed between the hits on infrequent target detection for EV, and the size of the interference effect for executive control in the percentage of errors, which indeed can be interpreted as a positive relation between the effectiveness in detecting infrequent targets and the effectiveness in selecting the target from the grouping with distractors. On the other hand, AV was specifically associated with the RT score of phasic alertness. Therefore, it might be possible that indeed AV and phasic alertness reflects two mechanisms that are implied in the regulation of the arousal levels of attention in different periods of time, either to increase briefly arousal (i.e., phasic alertness) or to sustain arousal over long time periods (i.e., AV) (S. E. Petersen & Posner, 2012; Posner & Petersen, 1990). In summary, this set of findings seems to further support with empirical evidence a distinction between vigilance components: whereas EV is further associated with attentional mechanisms modulating the overall effectiveness of responses and the mechanisms implied in the correct selection of the target from distractors, AV seems to be linked to attentional mechanisms involved in regulating the levels of arousal in different periods of time.

Different modulations for the EV and the AV decrement

Finally, along the present dissertation we have observed different modulations for EV and AV that seem to further support an empirical (and therefore theoretical) dissociation between vigilance components. In short, in Experimental Series 2, it was found that the cognitive loads of the task (i.e., performing a single, dual, or triple task) modulates importantly the decrement on the hits for EV, but not the most sensitive measure of AV, i.e., the progressive increment of RT variability. In addition, the largest mental fatigue was experienced after performing a single EV task (i.e., like the classical MCT or SART), in contrast with performing either a single AV task (i.e., like the PVT), a dual vigilance task (i.e., EV and AV) and a triple task like the ANTI-Vea. Altogether, these findings seems to suggest that EV is indeed a vigilance component more relative to a cognitive ability, which is experienced as subjectively stressful when performing long, monotonous, and intellectually unchallenging signal detection tasks (Warm et al., 2008), and that is modulated by concurrent working memory load when performing simultaneous tasks (Helton & Russell, 2011). AV seems instead to be an ability less cognitive demanding, as observed by the lower mental fatigue experienced after completing a single AV task like the PVT, and most importantly, the decrement of this component seems to be independent on the concurrent working memory load. It is important to note, however, that there might be other ways of maintaining high levels of preparation different from arousal levels – as in temporal orienting paradigms –, which indeed might rely on executive control, as shown with right frontal lesion patients who seems to be unable to voluntarily get ready for a short given time interval (Triviño, Arnedo, Lupiáñez, Chirivella, & Correa, 2011; Triviño, Correa, Arnedo, & Lupiáñez, 2010).

Lastly, regarding the neural mechanisms associated with vigilance components, we have already discussed that stimulating neurons excitability of the right PPC and DLPFC regions with anodal HD-tDCS effectively mitigates the EV decrement but does not modulates the AV one. In addition, and regarding some physiological mechanisms of the attentional networks system, in a recent study conducted in collaboration with sport scientists we have addressed the effects of caffeine intake and exercise intensity on the functioning of the attentional and vigilance components (Sanchis, Blasco, Luna, & Lupiañez, 2019). Note that, whereas previous research seems to be consistent on the moderating effects of caffeine to improve vigilance performance (Einöther & Giesbrecht, 2013; McLellan, Caldwell, & Lieberman, 2016), to date these effects have not been specifically addressed considering the EV and AV components dissociation. Moreover, there seems to be a considerable controversy in the literature regarding the specific effects of exercise intensity on attentional and vigilance functioning (Chang, Pesce, Chiang, Kuo, & Fong, 2015; de Sousa et al., 2018; Eddy et al., 2015; Sanabria et al., 2011; Smit, Eling, Hopman, & Coenen, 2005). Thus, to bring clarity on the precise effects of both caffeine intake and exercise intensity on the attentional vigilance components, we conducted a study wherein each participant performed the ANTI-Vea in six different experimental sessions, in which both: (a) caffeine, placebo, or no-treatment (i.e., control condition) was administered 45 min prior the experimental task, and (b) the ANTI-Vea was completed in a cycle-ergometer while performing one of two different levels of exercise intensity (i.e., light or moderate). In short, we observed dissociated effects of caffeine intake and exercise intensity over vigilance components: whereas moderate exercise seems to stabilize the RT of responses in EV across time on task, the effects of caffeine intake seems to modulate in particular the AV decrement independently on the exercise intensity (Sanchis et al., 2019).

Thus, in summary, it seems that EV and AV might be modulated by different neural and physiological mechanisms of the attentional networks system. Nevertheless, to deeper account on a theoretical and empirical dissociation between EV and AV, further research is still necessary.

Future Lines of Research

From a theoretical line of research, future studies should keep more deeply examining whether the existing models (i.e., the resources overload and the mind wandering model) are adequate frameworks to explain the vigilance decrement phenomenon (Smallwood & Schooler, 2006; Thomson, Besner, et al., 2015; Warm et al., 2008). Note that, in Chapter 4, we have partially concluded that neither the resources overload nor the mind-wandering model are completely adequate to explain: (a) the modulations observed for the EV decrement as a function of the cognitive loads of the task; and (b) the fact that the subjective mental fatigue experienced was larger after performing a single EV task than a dual task (in contrast with the predictions derived from the resources overload model), band the considerable increment in the mental fatigue after performing a triple task (thus in contrast with the predictions stated by the mind wandering account).

In addition, and importantly, although the resources control theory of mind wandering has been recently proposed as an integrative framework to overcome the theoretical and empirical limitations of the resources overload and mind wandering theories, it should be noted that this new model has been only theoretically developed. Therefore, experimental research is critically necessary to support the predictions stated by the resource control theory of mind wandering, in particular concerning: (a) the potential decrement of executive control across time on task; and (b) the role of executive control processes in modulating the attentional resources (i.e., towards the external activity or the internal unrelated thoughts) in vigilance tasks across time on task (Thomson, Besner, et al., 2015). Indeed, note that whereas in the General Discussion of Chapter 4 we have presented data that, with the ANTI-Vea (both the standard and the online version of the task analyzed in Chapter 5) the interference effect seems to increase across time on task (thus suggesting a progressive decrement of executive control), this effect does not specifically explain how executive control modulates permanently vigilance processes across time on task (Thomson, Besner, et al., 2015). Furthermore, to date, it remains unclear whether the AV component has a critical moderating role over executive control and/or EV across time on task (Langner & Eickhoff, 2013; Sarter et al., 2001). Thus, we strongly suggest that future models aiming at explaining the vigilance decrement phenomenon should take into account the theoretical distinction addressed in the present dissertation between EV and AV.

Moreover, new experimental research combining neuroimaging and/or non-invasive brain stimulation techniques with the ANTI-Vea task are critically necessary to provide additional evidence concerning both a theoretical and empirical dissociation between EV and AV. Therefore, as above-mentioned, we are conducting at present two new studies to overcome some of the methodological procedural limitations of Experimental Series 4 (Chapter 6) and 5 (Chapter 7). In particular, whereas in Experimental Series 4 the EEG signal was registered only at the baseline and post-stimulation periods with an 8 channels equipment, in a new ongoing study in our lab we are registering EEG signal with 128 high-density channels across all the experimental blocks of the ANTI-Vea task. Thus, with this new approach we expect to further dissociate both event-related potentials (Abundis-Gutiérrez et al., 2014; Galvao-Carmona et al., 2014; Neuhaus et al., 2010) and the shifts in electrical cortical rhythms (Boksem et al., 2005; Clayton et al., 2015; Hoedlmoser et al., 2011) associated with attentional and vigilance components performance. In addition, whereas in Experimental Series 5 the microstructural white matter connectivity was associated with the performance of attention and EV measured with the ANTI-V (Roca et al., 2011), we are conducting at present a new study wherein DWI data will be correlated with the attentional and vigilance components performance assessed with the ANTI-Vea task.

Altogether, we expect the future lines of research arising from the present dissertation to deeper investigate the behavioral patterns and neural mechanisms of the attentional networks system – and in particular the EV and AV components –, could also contribute to: (a) dissociating potential biomarkers for detecting clinical symptoms and/or improving clinical treatments on attentional deficits as, for instance, ADHD (Faraone et al., 2015); and (b) improving neurofeedback training and the use of effective countermeasures to mitigate the EV/AV decrement across time on task in applied contexts (Bartel, 2004; Basner et al., 2008; J. T. Nelson et al., 2014; Smyth, Maximova, & Jirsch, 2017).

Conclusions

The present dissertation aimed to address a theoretical and empirical dissociation between EV and AV as two different mechanisms of the attentional networks system. Thus, along the present dissertation, we have developed a theoretical analysis of previous literature wherein the concept of vigilance seems to be used in a broad sense for referring to different mechanisms of the alerting network. In addition, we conducted five experimental series to determine the behavioral patterns and neural mechanisms associated with the EV and AV in the context of the attentional networks system. A main conclusion of the present dissertation is that EV and AV can be indeed considered as two dissociated components: whereas EV refers to a cognitive ability for sustaining attention over extended periods of time to detect infrequent critical signals, AV seems to be the behavioral responsiveness of the arousal levels of attention for sustaining a fast reaction to stimuli from environment over long time periods without implementing much control over responses. Critically, we have developed a novel behavioral task, the ANTI-Vea, which is effective to assess within a single session a wide set of mechanisms of the attentional networks system, in particular: the independence and interactions of phasic alertness, orienting, and executive control, along with the EV and AV decrement across time on task. Importantly, for researchers interested in measuring attentional and vigilance components outside the lab in applied/clinical contexts, we have designed an open website that is publicly available to administer the online ANTI-Vea (https://www.ugr.es/~neurocog/Sitio_web/ANTI/). Finally, the present dissertation has contributed to a deeper examination of the neural mechanisms underlying the alerting network: whereas the right fronto-parietal cortical activity seems to modulate both the EV (but not the AV) decrement across time on task and the effectiveness of responses under a phasic alertness state, the microstructural connectivity of both the right dorsolateral prefrontal caudate tracts and the splenium of the corpus callosum seem to specifically underlie the phasic alertness functioning. We consider the present dissertation has contributed to clarify a controversial use of the concept of vigilance observed by addressing both a theoretical and empirical dissociation of EV and AV as two independent mechanisms of the attentional networks system.

Abstract

One of the central mechanisms supported by the attentional networks system (Petersen & Posner, 2012; Posner & Petersen, 1990) is the challenging ability of maintaining an adequate performance during extended periods of time. Over several decades, the maintenance of attention over long time periods has been conceptualized by cognitive and brain research as 'vigilance', and there has been a considerable interest in these research disciplines in examining why and how vigilance performance tends do decline across time on task (i.e., a widely-reported phenomenon that is known as the 'vigilance decrement') (Hancock, 2017; Scerbo, 1998).

An extended an integrative review of the literature drove us to consider that vigilance, rather than a single mechanism, can be conceived indeed as two different components of the attentional networks system (Langner & Eickhoff, 2013; Oken, Salinsky, & Elsas, 2006; Sarter, Givens, & Bruno, 2001). Whereas an executive component of vigilance (EV) can be characterized as a cognitive ability involved in monitoring and detecting rare but critical events over long time periods (Mackworth, 1948; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997; Thomson, Besner, & Smilek, 2016), an arousal component of vigilance (AV) seems to be particularly modulated by the excitability levels of attention for keeping a fast reaction to stimuli from environment without implementing much control over responses (Basner & Dinges, 2011; Lim & Dinges, 2008).

In the present dissertation, our general aim was to address a theoretical and empirical dissociation between EV and AV as two different mechanisms of the attentional networks system, to empirically investigate the conceptual dissociation of vigilance at the behavioral and neural level. Thus, motivated by the controversial use of the concept of vigilance in cognitive and brain research, we decided to conduct a theoretical analysis along all the chapters of the present dissertation, but mainly in the Introduction (Chapter 1) and the General Discussion (Chapter 8), to conceptually characterize EV and AV as two distinct behavioral and neural mechanisms of the attentional networks system. Then, to empirically analyze a potential dissociation between EV and AV, we conducted five experimental series aiming at addressing several specific objectives.

In particular, along Chapters 3 to 5, we analyzed the behavioral patterns of the EV and AV decrement within the context of the attentional networks system. To this end, a specific objective of the present dissertation was to develop new version of the attentional networks test, the ANTI-Vea task, to assess within a single session both vigilance components along with the independence and interactions of the classic attentional networks functions (i.e., phasic alertness, orienting, and executive control). Thus, in the experimental series conducted in Chapters 3 to 5, we have systematically observed that the novel ANTI-Vea task developed here: (a) is more adequate than traditional single, repetitive, and intellectually unchallenging vigilance tasks, to examine the cognitive mechanisms underlying the vigilance decrement phenomenon; (b) is more reliable than the former version of the task, the ANTI-V, to assess EV along with the classic attentional networks functions; and (c) is a suitable task to assess the behavioral patterns of the AV decrement and the EV decrement.

Furthermore, we seek the ANTI-Vea to be a useful tool for the scientific community interested in measuring the attentional and vigilance components in applied and/or clinical contexts. To this end, we developed a friendly and free website (https://www.ugr.es/~neurocog/Sitio_web/ANTI/) for administering the ANTI-Vea outside the lab. Note that, critically, in Chapter 5 we observed that the online ANTI-Vea is as effective as the standard ANTI-Vea (i.e., the version of the task administered under the typical lab conditions) to assess the EV and AV decrement along with the independence and interactions of the classic attentional components. In addition, in Chapter 5 we collected a relative large sample size ($N = 617$) to examine the split-half reliability of the attentional and vigilance scores of the ANTI-Vea, and we have observe that: (a) the ANTI-Vea is as reliable as former versions of the attentional networks in the assessment of the classic attentional components and EV (Ishigami & Klein, 2010; MacLeod et al., 2010; Roca, García-Fernández, Castro, & Lupiáñez, 2018); (b) the EV and AV components demonstrated a considerable reliability both with the standard and the online version of the task.

Finally, across Chapters 6 and 7, we aimed at further analyzing the neural mechanisms that modulates the human attentional networks (Petersen & Posner, 2012; Posner, Sheese, Odludaş, & Tang, 2006), with a particular interest in dissociating the brain circuits of the alerting network underlying the functioning of EV and AV components. In short, in the experimental series of Chapter 6, we have observed that online High-Definition transcranial current direct stimulation over the right fronto-parietal cortices activity mitigates the EV (but not the AV) decrement across time on task, and improves the effectiveness of responses under a phasic alertness state. In the experimental series of Chapter 7, we analyzed the microstructural white matter connectivity underlying the attentional networks system, and we observed that both the right dorsolateral prefrontal caudate tracts and the splenium of the corpus callosum seem to specifically support the phasic alertness functioning.

Altogether, the theoretical and empirical findings of the present dissertation seem to support that vigilance should not be considered as a single mechanism, and therefore it is better interpreted as two distinct components: the EV and the AV. Thus, we expect the present dissertation has contributed to clarify a controversial use of the concept of vigilance by proposing a theoretical and empirical dissociation of EV and AV as two independent mechanisms of the attentional networks system. Future lines of research may consider this dissociation for developing more adequate theoretical models aiming at explaining the vigilance decrement phenomenon, and to further determine the neural mechanisms underlying the EV and AV components with a potential use in clinical and applied contexts.

Resumen

Uno de los mecanismos centrales desarrollados por el sistema de redes atencionales (Petersen & Posner, 2012; Posner & Petersen, 1990) es la dificultosa habilidad de mantener un rendimiento adecuado durante períodos de tiempo extendido. Durante varias décadas, el mantenimiento de la atención durante largos períodos de tiempo se ha conceptualizado desde la investigación cognitiva y cerebral como la ‘vigilancia’, y ha habido un notable interés en estas disciplinas de investigación en examinar por qué y cómo la vigilancia tiende a disminuir conforme avanza el tiempo en la tarea (un fenómeno ampliamente reportado como ‘decremento de la vigilancia’) (Hancock, 2017; Scerbo, 1998).

Una extendida e integradora revisión de la literatura nos llevó a considerar que la vigilancia, más que ser un mecanismo único, podría ser entendida como dos componentes distintos dentro del sistema de redes atencionales (Langner & Eickhoff, 2013; Oken, Salinsky, & Elsas, 2006; Sarter, Givens, & Bruno, 2001). Mientras que un componente ejecutivo de la vigilancia (VE) puede caracterizarse como una habilidad cognitiva involucrada en monitorizar y detectar eventos críticos que sucede con poca frecuencia en largos períodos de tiempo (Mackworth, 1948; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997; Thomson, Besner, & Smilek, 2016), un componente de activación de la vigilancia (VA) parecería estar particularmente modulado por los niveles de excitabilidad de la atención para mantener una reacción veloz a los estímulos del entorno sin necesidad de implementar un control considerable sobre la ejecución de las respuestas (Basner & Dinges, 2011; Lim & Dinges, 2008).

En la presente tesis, nuestro objetivo general fue abordar una disociación teórica y empírica entre VE y VA considerándolos como dos componentes distintos dentro del sistema de redes atencionales, para así investigar empíricamente la disociación conceptual de la vigilancia a un nivel comportamental tanto como neural. Así, motivados por el uso controversial del concepto de vigilancia en la literatura de investigación cognitiva y cerebral, decidimos realizar un análisis teórico a lo largo de todos los capítulos de la presente tesis, pero principalmente en la Introducción (Capítulo 1) y la Discusión General (Capítulo 8), para caracterizar conceptualmente VE y VA como dos mecanismos comportamentales y neuronales distintos del sistema de redes atencionales. Luego, para analizar empíricamente una potencial disociación entre VE y VA, realizamos cinco series experimentales que abordaron diferentes objetivos específicos.

En particular, entre los Capítulos 3 a 5, analizamos los patrones comportamentales del decremento de VE y VA dentro del contexto del sistema de redes atencionales. Para poder llevar adelante este análisis, un objetivo específico de la presente tesis fue desarrollar una nueva versión del test de redes atencionales, la tarea ANTI-Vea, para medir dentro de una sola sesión experimental los dos componentes de la vigilancia junto con la independencia e interacciones de las funciones clásicas de las redes atencionales (es decir, alerta fásica, orientación, y control ejecutivo). Así, en las series experimentales desarrolladas en los Capítulos 3 a 5, hemos observado sistemáticamente que la novedosa tarea ANTI-Vea desarrollada en el presente trabajo: (a) es más adecuada que las típicas tareas de vigilancia de carácter simple, repetitivo, y cognitivamente poco demandantes, para examinar los mecanismos cognitivos subyacentes al fenómeno del decremento de la vigilancia; (b) es más confiable que la versión anterior de la tarea, la ANTI-V, para medir la VE junto con las funciones clásicas de las redes atencionales; y (c) es una tarea adecuada para evaluar los patrones comportamentales del decremento de VA y VE.

Además, buscamos que la tarea ANTI-Vea sea una herramienta útil para la comunidad científica interesada en medir los componentes de atención y vigilancia en contextos clínicos y/o aplicados. Para ello, desarrollamos un sitio web de uso amigable y de libre acceso (https://www.ugr.es/~neurocog/Sitio_web/ANTI/) para administrar la tarea ANTI-Vea por fuera del laboratorio. Es importante tener en cuenta que, de manera crítica, en el capítulo 5 observamos que la ANTI-Vea en línea es tan efectiva como la ANTI-Vea estándar (es decir, la versión administrada en las condiciones típicas de laboratorio) para medir el decremento de VE y VA junto con la independencia e interacciones de los componentes de atención clásicos. Más aún, en el Capítulo 5 recolectamos datos de una muestra relativamente grande (N = 617) para examinar la confiabilidad de mitad-dividida de los puntajes atencionales y de vigilancia de la tarea ANTI-Vea, y observamos que: (a) la tarea ANTI-Vea es tan confiable como las versiones anteriores del test de redes atencionales en la evaluación de los componentes de atención clásicos y la VE (Ishigami & Klein, 2010; MacLeod et al., 2010; Roca, García-Fernández, Castro, & Lupiáñez, 2018); y (b) los componentes VE y VA demostraron una confiabilidad considerable tanto con la versión estándar como con la versión en línea.

Finalmente, en los Capítulos 6 y 7, nos propusimos contribuir al análisis de los mecanismos neuronales que modulan las redes humanas de la atención (Petersen & Posner, 2012; Posner, Sheese, Odludaş, & Tang, 2006), con un interés particular en disociar los circuitos cerebrales de la red de alerta que serían subyacentes del funcionamiento de los componentes VE y VA. En resumen, en la serie experimental del Capítulo 6, observamos que la estimulación eléctrica transcraneal directa en línea de alta definición aplicada sobre las cortezas fronto-parietales derechas reduce el decremento de VE (pero no de VA) y mejora la efectividad de las respuestas que se ejecutan bajo un estado de alerta fásica. En la serie experimental del Capítulo 7, analizamos la conectividad micro-estructural de la sustancia blanca subyacente al sistema de redes atencionales, y observamos que tanto los tractos caudados prefrontales dorso-laterales del hemisferio derecho como el splenium del cuerpo calloso parecen soportar específicamente el funcionamiento del alerta fásica.

En conjunto, los hallazgos teóricos y empíricos de la presente tesis parecen apoyar la idea de que la vigilancia no debe ser considerada como un mecanismo único, y por lo tanto es mejor interpretada como dos componentes distintos: VE y VA. Así, esperamos que la presente tesis haya contribuido a aclarar un uso controversial del concepto de vigilancia mediante la propuesta de una disociación teórica y empírica de VE y VA como dos mecanismos independientes del sistema de redes atencionales. En futuras líneas de investigación, debería considerarse esta disociación con el objetivo de desarrollar modelos teóricos que busquen explicar de una manera más apropiada el fenómeno del decremento en la vigilancia, y para determinar los mecanismos neuronales subyacentes a los componentes VE y VA con un potencial uso en contextos clínicos y aplicados.

References

Abundis-Gutiérrez, A., Checa, P., Castellanos, C., & Rosario Rueda, M. (2014). Electrophysiological correlates of attention networks in childhood and early adulthood. *Neuropsychologia*, *57*(1), 78–92. https://doi.org/10.1016/j.neuropsychologia.2014.02.013

Adams, J. A. (1987). Criticisms of Vigilance Research: A Discussion. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *29*(6), 737–740. https://doi.org/10.1177/001872088702900612

Alexander, D. C. (2005). Multiple-Fiber Reconstruction Algorithms for Diffusion MRI. *Annals of the New York Academy of Sciences*, *1064*(1), 113–133. https://doi.org/10.1196/annals.1340.018

Asanowicz, D., & Marzecová, A. (2017). Differential effects of phasic and tonic alerting on the efficiency of executive attention. *Acta Psychologica*, *176*(March), 58–70. https://doi.org/10.1016/j.actpsy.2017.03.004

Balakrishnan, J. D. (1998). Measures and Interpretations of Vigilance Performance: Evidence against the Detection Criterion. *Human Factors*, *40*(4), 601–623.

Bartel, P. (2004). Attention and working memory in resident anaesthetists after night duty: group and individual effects. *Occupational and Environmental Medicine*, *61*(2), 167–170. https://doi.org/10.1136/oem.2002.006197

Basner, M., & Dinges, D. F. (2011). Maximizing sensitivity of the psychomotor vigilance test (PVT) to sleep loss. *Sleep*, *34*(5), 581–591.

Basner, M., Mollicone, D., & Dinges, D. F. (2011). Validity and sensitivity of a brief psychomotor vigilance test (PVT-B) to total and partial sleep deprivation. *Acta Astronautica*, *69*(11–12), 949–959. https://doi.org/10.1016/j.actaastro.2011.07.015

Basner, M., Rao, H., Goel, N., & Dinges, D. F. (2013). Sleep deprivation and neurobehavioral dynamics. *Current Opinion in Neurobiology*, *23*(5), 854–863. https://doi.org/10.1016/j.conb.2013.02.008

Basner, M., Rubinstein, J., Fomberstein, K. M., Coble, M. C., Ecker, A., Avinash, D., & Dinges, D. F. (2008). Effects of night work, sleep loss and time on task on simulated threat detection performance. *Sleep*, *31*(9), 1251–1259.

Bastien, C., Vallières, A., Morin, C. M., Ford, D. ., Kamerow, D. ., Mellinger, G. ., … Bliwise, D. . (2001). Validation of the Insomnia Severity Index as an outcome measure for insomnia research. *Sleep Medicine*, *2*(4), 297–307. https://doi.org/10.1016/S1389-9457(00)00065-4

Blatter, K., Graw, P., Münch, M., Knoblauch, V., Wirz-Justice, A., & Cajochen, C. (2006). Gender and age differences in psychomotor vigilance performance under differential sleep pressure conditions. *Behavioural Brain Research*, *168*(2), 312–317. https://doi.org/10.1016/j.bbr.2005.11.018

Boksem, M. A. S., Meijman, T. F., & Lorist, M. M. (2005). Effects of mental fatigue on attention: An ERP study. *Cognitive Brain Research*, *25*(1), 107–116. https://doi.org/10.1016/j.cogbrainres.2005.04.011

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict Monitoring and Cognitive Control. *Pyschological Review*, *108*(3), 624–652. https://doi.org/10.1037//0033-295X.I08.3.624

Botvinick, M. M., Cohen, J. D., & Carter, C. S. (2004). Conflict monitoring and anterior cingulate cortex: an update. *Trends in Cognitive Sciences*, *8*(12), 539–546. https://doi.org/10.1016/j.tics.2004.10.003

Braver, T. S. (2012). The variable nature of cognitive control: A dual mechanisms framework. *Trends in Cognitive Sciences*, *16*(2), 106–113. https://doi.org/10.1016/j.tics.2011.12.010

Broadbent, D. E., Cooper, P. F., FitzGerald, P., & Parkes, K. R. (1982). The cognitive failures questionnaire (CFQ) and its correlates. *British Journal of Clinical Psychology*, *21*(1), 1–16. https://doi.org/10.1111/j.2044-8260.1982.tb01421.x

Buckner, R. L., Andrews-Hanna, J. R., & Schacter, D. L. (2008). The brain’s default network: Anatomy, function, and relevance to disease. *Annals of the New York Academy of Sciences*, *1124*, 1–38. https://doi.org/10.1196/annals.1440.011

Bukowski, M., Asanowicz, D., Marzecová, A., & Lupiáñez, J. (2015). Limits of control: The effects of uncontrollability experiences on the efficiency of attentional control. *Acta Psychologica*, *154*, 43–53. https://doi.org/10.1016/j.actpsy.2014.11.005

Burton, L., Pfaff, D., Bolt, N., Hadjikyriacou, D., Silton, N., Kilgallen, C., … Allimant, J. (2010). Effects of gender and personality on the Conners Continuous Performance Test. *Journal of Clinical and Experimental Neuropsychology*, *32*(1), 66–70. https://doi.org/10.1080/13803390902806568

Callejas, A., Lupiáñez, J., Funes, M. J., & Tudela, P. (2005). Modulations among the alerting, orienting and executive control networks. *Experimental Brain Research*, *167*(1), 27–37. https://doi.org/10.1007/s00221-005-2365-z

Callejas, A., Lupiáñez, J., & Tudela, P. (2004). The three attentional networks: on their independence and interactions. *Brain and Cognition*, *54*(3), 225–227. https://doi.org/10.1016/j.bandc.2004.02.012

Casagrande, M., Marotta, A., Canepone, V., Spagna, A., Rosa, C., Dimaggio, G., & Pasini, A. (2017). Dysfunctional personality traits in adolescence: effects on alerting, orienting and executive control of attention. *Cognitive Processing*, *18*(2), 183–193. https://doi.org/10.1007/s10339-017-0797-6

Catani, M., & Thiebaut de Schotten, M. (2008). A diffusion tensor imaging tractography atlas for virtual in vivo dissections. *Cortex*, *44*(8), 1105–1132. https://doi.org/10.1016/j.cortex.2008.05.004

Catani, M., & Thiebaut de Schotten, M. (2012). *Atlas of human brain connections*. New York: Oxford University Press.

Chan, R. C. (2001). A further study on the sustained attention response to task (SART): the effect of age, gender and education. *Brain Injury*, *15*(9), 819–829. https://doi.org/10.1080/02699050110034325

Chang, Y.-K., Pesce, C., Chiang, Y.-T., Kuo, C.-Y., & Fong, D. (2015). Antecedent acute cycling exercise affects attention control: an ERP study using attention network test. *Frontiers in Human Neuroscience*, *9*(April), 1–13. https://doi.org/10.3389/fnhum.2015.00156

Chiang, H.-L., Chen, Y.-J., Lo, Y.-C., Tsen, W.-Y. I., & Gau, S. S.-F. (2015). Altered white matter tract property related to impaired focused attention, sustained attention, cognitive impulsivity and vigilance in attention-deficit/ hyperactivity disorder. *Journal of*

Psychiatry & Neuroscience, *40*(5), 325–335. https://doi.org/10.1503/jpn.140106

Chica, A. B., Bartolomeo, P., & Lupiáñez, J. (2013). Two cognitive and neural systems for endogenous and exogenous spatial attention. *Behavioural Brain Research*, *237*(237), 107–123. https://doi.org/10.1016/j.bbr.2012.09.027

Claypoole, V. L., Neigel, A. R., Fraulini, N. W., Hancock, G. M., & Szalma, J. L. (2018). Can vigilance tasks be administered online? A replication and discussion. *Journal of Experimental Psychology: Human Perception and Performance*, *44*(9), 1348–1355. https://doi.org/10.1037/xhp0000538

Clayton, M. S., Yeung, N., & Cohen Kadosh, R. (2015). The roles of cortical oscillations in sustained attention. *Trends in Cognitive Sciences*, *19*(4), 188–195. https://doi.org/10.1016/j.tics.2015.02.004

Clayton, M. S., Yeung, N., & Cohen Kadosh, R. (2019). Electrical stimulation of alpha oscillations stabilizes performance on visual attention tasks. *Journal of Experimental Psychology: General*, *148*(2), 203–220. https://doi.org/10.1037/xge0000502

Coffman, B. A., Clark, V. P., & Parasuraman, R. (2014). Battery powered thought: Enhancement of attention, learning, and memory in healthy adults using transcranial direct current stimulation. *NeuroImage*, *85*, 895–908. https://doi.org/10.1016/j.neuroimage.2013.07.083

Coffman, B. A., Trumbo, M. C., & Clark, V. P. (2012). Enhancement of object detection with transcranial direct current stimulation is associated with increased attention. *BMC Neuroscience*, *13*(1), 108. https://doi.org/10.1186/1471-2202-13-108

Conners, C. (2000). *Conners' Continuous Performance Test II*. Toronto, Canada: Multi-Health Systems.

Corbetta, M., Patel, G., & Shulman, G. L. (2008). The Reorienting System of the Human Brain: From Environment to Theory of Mind. *Neuron*, *58*(3), 306–324. https://doi.org/10.1016/j.neuron.2008.04.017

Danckert, J., & Merrifield, C. (2016). Boredom, sustained attention and the default mode network. *Experimental Brain Research*, 1–12. https://doi.org/10.1007/s00221-016-4617-5

Datta, A., Bansal, V., Diaz, J., Patel, J., Reato, D., & Bikson, M. (2009). Gyri-precise head model of transcranial direct current stimulation: Improved spatial focality using a ring electrode versus conventional rectangular pad. *Brain Stimulation*, *2*(4), 201-207.e1. https://doi.org/10.1016/j.brs.2009.03.005

de Sousa, A. F. M., Medeiros, A. R., Benitez-Flores, S., Del Rosso, S., Stults-Kolehmainen, M., & Boullosa, D. A. (2018). Improvements in Attention and Cardiac Autonomic Modulation After a 2-Weeks Sprint Interval Training Program: A Fidelity Approach. *Frontiers in Physiology*, *9*(March), 1–9. https://doi.org/10.3389/fphys.2018.00241

Dedoncker, J., Brunoni, A. R., Baeken, C., & Vanderhasselt, M.-A. (2016). A Systematic Review and Meta-Analysis of the Effects of Transcranial Direct Current Stimulation (tDCS) Over the Dorsolateral Prefrontal Cortex in Healthy and Neuropsychiatric Samples: Influence of Stimulation Parameters. *Brain Stimulation*, *9*(4), 501–517. https://doi.org/10.1016/j.brs.2016.04.006

Dell'Acqua, F., Simmons, A., Williams, S. C. R., & Catani, M. (2013). Can spherical deconvolution provide more information than fiber orientations? Hindrance modulated orientational anisotropy, a true-tract specific index to characterize white matter diffusion. *Human Brain Mapping*, *34*(10), 2464–2483. https://doi.org/10.1002/hbm.22080

Derryberry, D., & Reed, M. A. (2002). Anxiety-related attentional biases and their regulation by attentional control. *Journal of Abnormal Psychology*, *111*(2), 225–236. https://doi.org/10.1037/0021-843X.111.2.225

Dosenbach, N. U. F., Fair, D. A., Cohen, A. L., Schlaggar, B. L., & Petersen, S. E. (2008). A dual-networks architecture of top-down control. *Trends in Cognitive Sciences*, *12*(3), 99–105. https://doi.org/10.1016/j.tics.2008.01.001

Drummond, S. P. a, Bischoff-Grethe, A., Dinges, D. F., Ayalon, L., Mednick, S. C., & Meloy, M. J. (2005). The neural basis of the psychomotor vigilance task. *Sleep*, *28*(9), 1059–1068.

Eddy, M. D., Hasselquist, L., Giles, G., Hayes, J. F., Howe, J., Rourke, J., … Mahoney, C. R. (2015). The effects of load carriage and physical fatigue on cognitive performance. *PLoS ONE*, *10*(7), 1–14. https://doi.org/10.1371/journal.pone.0130817

Einöther, S. J. L., & Giesbrecht, T. (2013). Caffeine as an attention enhancer: reviewing existing assumptions. *Psychopharmacology*, *225*(2), 251–274. https://doi.org/10.1007/s00213-012-2917-4

Epling, S. L., Russell, P. N., & Helton, W. S. (2016). A new semantic vigilance task: vigilance decrement, workload, and sensitivity to dual-task costs. *Experimental Brain Research*, *234*(1), 133–139. https://doi.org/10.1007/s00221-015-4444-0

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics*, *16*(1), 143–149. https://doi.org/10.3758/BF03203267

Esterman, M., Noonan, S. K., Rosenberg, M., & Degutis, J. (2013). In the zone or zoning out? Tracking behavioral and neural fluctuations during sustained attention. *Cerebral Cortex*, *23*(11), 2712–2723. https://doi.org/10.1093/cercor/bhs261

Fan, J, Gu, X., Guise, K. G., Liu, X., Fossella, J., Wang, H., & Posner, M. I. (2009). Testing the behavioral interaction and integration of attentional networks. *Brain and Cognition*, *70*(2), 209–220. https://doi.org/10.1016/j.bandc.2009.02.002

Fan, J, McCandliss, B. D., Fossella, J., Flombaum, J. I., & Posner, M. I. (2005). The activation of attentional networks. *NeuroImage*, *26*(2), 471–479. https://doi.org/10.1016/j.neuroimage.2005.02.004

Fan, J, McCandliss, B. D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience*, *14*(3), 340–347. https://doi.org/10.1162/089892902317361886

Fan, J, Wu, Y., Fossella, J. a, & Posner, M. I. (2001). Assessing the heritability of attentional networks. *BMC Neuroscience*, *2*, 14. https://doi.org/10.1186/1471-2202-2-14

Fan, Jin, & Posner, M. (2004). Human attentional networks. *Psychiatrische Praxis*, *31*(Supplement 2), S210–S214. https://doi.org/10.1055/s-2004-828484

Faraone, S. V., Asherson, P., Banaschewski, T., Biederman, J., Buitelaar, J. K., Ramos-Quiroga, J. A., … Franke, B. (2015). Attention-deficit/hyperactivity disorder. *Nature*

Reviews Disease Primers, *1*, 15020. https://doi.org/10.1038/nrdp.2015.20

Fernandez-Duque, D., & Posner, M. I. (1997). Relating the mechanisms of orienting and alerting. *Neuropsychologia*, *35*(4), 477–486. https://doi.org/10.1016/S0028-3932(96)00103-0

Fertonani, A., Ferrari, C., & Miniussi, C. (2015). What do you feel if I apply transcranial electric stimulation? Safety, sensations and secondary induced effects. *Clinical Neurophysiology*, *126*(11), 2181–2188. https://doi.org/10.1016/j.clinph.2015.03.015

Fertonani, A., & Miniussi, C. (2017). Transcranial Electrical Stimulation: What We Know and Do Not Know About Mechanisms. *The Neuroscientist*, *23*(2), 109–123. https://doi.org/10.1177/1073858416631966

Fortenbaugh, F. C., Degutis, J., & Esterman, M. (2017). Recent theoretical, neural, and clinical advances in sustained attention research. *Annals of the New York Academy of Sciences*, *1396*, 70–91. https://doi.org/10.1111/nyas.13318

Fortenbaugh, F. C., Degutis, J., Germine, L., Wilmer, J. B., Grosso, M., Russo, K., & Esterman, M. (2015). Sustained attention across the life span in a sample of 10,000: Dissociating ability and strategy. *Psychological Science*, *26*(9), 1497–1510. https://doi.org/10.1177/0956797615594896

Franco, A., Malhotra, N., & Simonovits, G. (2014). Publication bias in the social sciences: Unlocking the file drawer. *Science*, *345*(6203), 1502–1505. https://doi.org/10.1126/science.1255484

Fraulini, N. W., Hancock, G. M., Neigel, A. R., Claypoole, V. L., & Szalma, J. L. (2017). A Critical Examination of the Research and Theoretical Underpinnings Discussed in Thomson, Besner, and Smilek (2016). *Psychological Review*, *124*(4), 525–531. https://doi.org/10.1037/rev0000066

Funes, M. J., & Lupiáñez, J. (2003). La teoría atencional de Posner: una tarea para medir las funciones atencionales de Orientación , Alerta y Control Cognitivo y la interacción entre ellas. *Psicothema*, *15*(2), 260–266.

Funes, M. J., Lupiáñez, J., & Humphreys, G. (2010). Analyzing the generality of conflict adaptation effects. *Journal of Experimental Psychology. Human Perception and Performance*, *36*(1), 147–161. https://doi.org/10.1037/a0017598

Galvao-Carmona, A., González-Rosa, J. J., Hidalgo-Muñoz, A. R., Páramo, D.,
Bení-tez, M. L., Izquierdo, G., & Vázquez-Marrufo, M. (2014). Disentangling the attention network test: behavioral, event related potentials, and neural source analyses. *Frontiers in Human Neuroscience*, *8*(813), 1–16. https://doi.org/10.3389/fnhum.2014.00813

Gong, G., Jiang, T., Zhu, C., Zang, Y., Wang, F., Xie, S., … Guo, X. (2005). Asymmetry analysis of cingulum based on scale-invariant parameterization by diffusion tensor imaging. *Human Brain Mapping*, *24*(2), 92–98. https://doi.org/10.1002/hbm.20072

Greene, D. J., Barnea, A., Herzberg, K., Rassis, A., Neta, M., Raz, A., & Zaidel, E. (2008). Measuring attention in the hemispheres: The lateralized attention network test (LANT). *Brain and Cognition*, *66*, 21–31. https://doi.org/10.1016/j.bandc.2007.05.003

Grier, J. B. (1971). Nonparametric indexes for sensitivity and bias: computing formulas. *Psychological Bulletin*, *75*(6), 424–429. https://doi.org/10.1037/h0031246

Grier, R. A., Warm, J. S., Dember, W. N., Matthews, G., Galinsky, T. L., Szalma, J. L., & Parasuraman, R. (2003). The Vigilance Decrement Reflects Limitations in Effortful Attention, Not Mindlessness. *Human Factors*, *45*(3), 349–359. https://doi.org/10.1518/hfes.45.3.349.27253

Hancock, P. A. (2017). On the Nature of Vigilance. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *59*(1), 35–43. https://doi.org/10.1177/0018720816655240

Harrell, F. E. J. (2018). Hmisc: Harrell Miscellaneous. R package version 4.1-1. Retrieved from https://cran.r-project.org/package=Hmisc

Hashimoto, M., Kumashiro, M., & Miyake, S. (2003). Effects of Screen Size and Task Difficulty on Vigilance Performance of Older Adults. *Journal of UOEH*, *25*(4), 375–386. https://doi.org/10.7888/juoeh.25.375

Head, J., & Helton, W. S. (2014). Sustained attention failures are primarily due to sustained cognitive load not task monotony. *Acta Psychologica*, *153*, 87–94. https://doi.org/10.1016/j.actpsy.2014.09.007

Helton, W. S. (2009). Impulsive responding and the sustained attention to response task. *Journal of Clinical and Experimental Neuropsychology*, *31*(1), 39–47. https://doi.org/10.1080/13803390801978856

Helton, W. S., Head, J., & Russell, P. N. (2011). Reliable- and unreliable-warning cues in the Sustained Attention to Response Task. *Experimental Brain Research*, *209*(3), 401–407. https://doi.org/10.1007/s00221-011-2563-9

Helton, W. S., Kern, R. P., & Walker, D. R. (2009). Conscious thought and the sustained attention to response task. *Consciousness and Cognition*, *18*(3), 600–607. https://doi.org/10.1016/j.concog.2009.06.002

Helton, W. S., & Russell, P. N. (2011). Working memory load and the vigilance decrement. *Experimental Brain Research*, *212*(3), 429–437. https://doi.org/10.1007/s00221-011-2749-1

Helton, W. S., & Russell, P. N. (2015). Rest is best: The role of rest and task interruptions on vigilance. *Cognition*, *134*, 165–173. https://doi.org/10.1016/j.cognition.2014.10.001

Helton, W. S., & Russell, P. N. (2017). Rest Is Still Best: The Role of the Qualitative and Quantitative Load of Interruptions on Vigilance. *Human Factors*, *59*(1), 91–100. https://doi.org/10.1177/0018720816683509

Helton, W. S., Weil, L., Middlemiss, A., & Sawers, A. (2010). Global interference and spatial uncertainty in the Sustained Attention to Response Task (SART). *Consciousness and Cognition*, *19*(1), 77–85. https://doi.org/10.1016/j.concog.2010.01.006

Hoedlmoser, K., Griessenberger, H., Fellinger, R., Freunberger, R., Klimesch, W., Gruber, W., & Schabus, M. (2011). Event-related activity and phase locking during a psychomotor vigilance task over the course of sleep deprivation. *Journal of Sleep Research*, *20*(3), 377–385. https://doi.org/10.1111/j.1365-2869.2010.00892.x

Huang, Y., Datta, A., Bikson, M., & Parra, L. C. (2017). Realistic vOlumetric-Approach to Simulate Transcranial Electric Stimulation — ROAST — a fully automated open-source pipeline. *BioRXiv*, 217331. https://doi.org/10.1101/217331

Huertas, F., Ballester, R., Gines, Hamidi, K. A., Moratal, C., & Lupiáñez, J. (2019). Relative age effect in sport environment. Role of physical fitness and cognitive function in youth football players. *Manuscript Submitted for Publicaction*.

Hunter, J. D. (2007). Matplotlib: A 2D graphics enviroment. *Computing In Science & Engineering*, *9*(3), 90–95. https://doi.org/10.1109/MCSE.2007.55

Hurley, R., & Machado, L. (2017). Using tDCS priming to improve brain function: Can metaplasticity provide the key to boosting outcomes? *Neuroscience and Biobehavioral Reviews*, *83*(September), 155–159. https://doi.org/10.1016/j.neubiorev.2017.09.029

Ishigami, Y., Eskes, G. A., Tyndall, A. V, Longman, R. S., Drogos, L. L., & Pulin, M. J. (2016). The Attention Network Test-Interaction (ANT-I): reliability and validity in healthy older adults. *Experimental Brain Research*, *234*(3), 815–827. https://doi.org/10.1007/s00221-015-4493-4

Ishigami, Y., & Klein, R. M. (2010). Repeated measurement of the components of attention using two versions of the Attention Network Test (ANT): stability, isolability, robustness, and reliability. *Journal of Neuroscience Methods*, *190*(1), 117–128. https://doi.org/10.1016/j.jneumeth.2010.04.019

Jacoby, N., & Lavidor, M. (2018). Null tDCS Effects in a Sustained Attention Task: The Modulating Role of Learning. *Frontiers in Psychology*, *9*(APR), 1–9. https://doi.org/10.3389/fpsyg.2018.00476

Jarosz, A. F., & Wiley, J. (2014). What Are the Odds? A Practical Guide to Computing and Reporting Bayes Factors. *The Journal of Problem Solving*, *7*(1), 2–9. https://doi.org/10.7771/1932-6246.1167

JASP, T. (2018). JASP (Version 0.9.0.0). Retrieved from https://jasp-stats.org/

Jonathon, E. W., Maarten, L., Tahira, M., Ly, A., Verhagen, J., Selker, R., … Morey, R. D. (2018). Bayesian inference for psychology . Part II : Example applications with JASP, 58–76. https://doi.org/10.3758/s13423-017-1323-7

Jones, D. K., & Leemans, A. (2011). Diffusion tensor imaging. *Methods in Molecular Biology*, *711*(2), 127–144. https://doi.org/10.1007/978-1-61737-992-5_6

Kahneman, D. (1973). *Attention and Effort*. New Jersey: Prentice-Hall Englewood Cliffs.

Kim, M. S., & Cave, K. R. (1999). Top-down and bottom-up attentional control: On the nature of interference from a salient distractor. *Perception and Psychophysics*, *61*(6), 1009–1023. https://doi.org/10.3758/BF03207609

Krause, A. J., Simon, E. Ben, Mander, B. A., Greer, S. M., Saletin, J. M., Goldstein-Piekarski, A. N., & Walker, M. P. (2017). The sleep-deprived human brain. *Nature Reviews Neuroscience*, *18*(7), 404–418. https://doi.org/10.1038/nrn.2017.55

Kuo, H.-I., Bikson, M., Datta, A., Minhas, P., Paulus, W., Kuo, M.-F., & Nitsche, M. A. (2013). Comparing Cortical Plasticity Induced by Conventional and High-Definition 4 × 1 Ring tDCS: A Neurophysiological Study. *Brain Stimulation*, *6*(4), 644–648. https://doi.org/10.1016/j.brs.2012.09.010

Kusnir, F., Chica, A. B., Mitsumasu, M. A., & Bartolomeo, P. (2011). Phasic auditory alerting improves visual conscious perception. *Consciousness and Cognition*, *20*(4), 1201–1210. https://doi.org/10.1016/j.concog.2011.01.012

Lamond, N., Dawson, D., & Roach, G. D. (2005). Fatigue assessment in the field: Validation of a hand-held electronic psychomotor vigilance task. *Aviation, Space, and Environmental Medicine*, *76*(5), 486–489.

Lamond, N., Jay, S. M., Dorrian, J., Ferguson, S. a, Roach, G. D., & Dawson, D. (2008). The sensitivity of a palm-based psychomotor vigilance task to severe sleep loss. *Behavior Research Methods*, *40*(1), 347–352. https://doi.org/10.3758/BRM.40.1.347

Langner, R., & Eickhoff, S. B. (2013). Sustaining attention to simple tasks: A meta-analytic review of the neural mechanisms of vigilant attention. *Psychological Bulletin*, *139*(4), 870–900. https://doi.org/10.1037/a0030694

Le Bihan, D., Mangin, J. F., Poupon, C., Clark, C. a, Pappata, S., Molko, N., & Chabriat, H. (2001). Diffusion tensor imaging: concepts and applications. *Journal of Magnetic Resonance Imaging : JMRI*, *13*(4), 534–546. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11276097

Lebel, C., Walker, L., Leemans, A., Phillips, L., & Beaulieu, C. (2008). Microstructural maturation of the human brain from childhood to adulthood. *NeuroImage*, *40*(3), 1044–1055. https://doi.org/10.1016/j.neuroimage.2007.12.053

Lee, I. S., Bardwell, W. A., Ancoli-Israel, S., & Dimsdale, J. E. (2010). Number of lapses during the psychomotor vigilance task as an objective measure of fatigue. *Journal of Clinical Sleep Medicine*, *6*(2), 163–168.

Leemans, A., Jeurissen, B., Sijbers, J., & Jones, D. K. (2009). ExploreDTI: A Graphical Toolbox for Processing, Analyzing, and Visualizing Diffusion MR Data. In *17th Annual Meeting of Intl Soc Mag Reson Med* (p. 3537). Hawaii.

Lichstein, K. L., Riedel, B. W., & Richman, S. L. (2000). The Mackworth Clock Test: A Computerized Version. *The Journal of Psychology*, *134*(2), 153–161. https://doi.org/10.1080/00223980009600858

Lim, J., & Dinges, D. F. (2008). Sleep deprivation and vigilant attention. *Annals of the New York Academy of Sciences*, *1129*, 305–322. https://doi.org/10.1196/annals.1417.002

Lo, O.-Y., van Donkelaar, P., & Chou, L.-S. (2019). Effects of transcranial direct current stimulation over right posterior parietal cortex on attention function in healthy young adults. *European Journal of Neuroscience*, (January), 1–9. https://doi.org/10.1111/ejn.14349

Loh, S., Lamond, N., Dorrian, J., Roach, G., & Dawson, D. (2004). The validity of psychomotor vigilance tasks of less than 10-minute duration. *Behavior Research Methods, Instruments, & Computers*, *36*(2), 339–346. https://doi.org/10.3758/BF03195580

Luna, F. G., Barttfeld, P., Martín-Arévalo, E., & Lupiáñez, J. (2019). Disentangling the analytical biases, attentional components, and cognitive loads of the vigilance decrement. *Manuscript Submitted for Publication*.

Luna, F. G., Lupiáñez, J., & Martín-Arévalo, E. (2019). Microstructural white matter connectivity and the attentional networks system. *Manuscript in Preparation*.

Luna, F. G., Marino, J., Roca, J., & Lupiáñez, J. (2018). Executive and arousal vigilance decrement in the context of the attentional networks: The ANTI-Vea task. *Journal of Neuroscience Methods*, *306*, 77–87. https://doi.org/10.1016/j.jneumeth.2018.05.011

Luna, F. G., Martín-Arévalo, E., Foa Torres, G., & Lupiáñez, J. (2019). White matter connectivity underlying the attentional and vigilance components. *Manuscript in Preparation*.

Luna, F. G., Roca, J., Martín-Arévalo, E., & Lupiáñez, J. (2019). The split-half reliability of the standard and the online ANTI-Vea. *Manuscript in Preparation*.

Luna, F. G., Román-Caballero, R., Barttfeld, P., Lupiáñez, J., & Martín-Arévalo, E. (2019). A High-Definition tDCS and EEG study on attention and vigilance: Brain stimulation mitigates the executive but not the arousal vigilance decrement. *Manuscript in Preparation2*.

Luna, F. G., Telga, M., Vadillo, M. A., & Lupiáñez, J. (2019). Concurrent working memory load may increase or reduce cognitive interference depending on the attentional set. *Manuscript Submitted for Publicaction in Journal of Experimental Psychology: Human Perception and Performance*.

Mackworth, N. H. (1948). The Breakdown of Vigilance during Prolonged Visual Search. *Quarterly Journal of Experimental Psychology*, *1*(1), 6–21. https://doi.org/10.1080/17470214808416738

MacLeod, J. W., Lawrence, M. A., McConnell, M. M., Eskes, G. A., Klein, R. M., & Shore, D. I. (2010). Appraising the ANT: Psychometric and theoretical considerations of the Attention Network Test. *Neuropsychology*, *24*(5), 637–651. https://doi.org/10.1037/a0019803

Makris, N., Kennedy, D. N., McInerney, S., Sorensen, a G., Wang, R., Caviness, V. S., & Pandya, D. N. (2005). Segmentation of subcomponents within the superior longitudinal fascicle in humans: a quantitative, in vivo, DT-MRI study. *Cerebral Cortex*, *15*(6), 854–869. https://doi.org/10.1093/cercor/bhh186

Marotta, A., Chiaie, R. D., Spagna, A., Bernabei, L., Sciarretta, M., Roca, J., … Casagrande, M. (2015). Impaired conflict resolution and vigilance in euthymic bipolar disorder. *Psychiatry Research*, *229*(1–2), 490–496. https://doi.org/10.1016/j.psychres.2015.06.026

Martella, D., Manzanares, S., Campoy, G., Roca, J., Antúnez, C., & Fuentes, L. J. (2014). Phasic and tonic alerting in mild cognitive impairment: A preliminary study. *Experimental Gerontology*, *49*(1), 35–39. https://doi.org/10.1016/j.exger.2013.11.001

Masson, M. E. J. (2011). A tutorial on a practical Bayesian alternative to null-hypothesis significance testing. *Behavior Research Methods*, *43*(3), 679–690. https://doi.org/10.3758/s13428-010-0049-5

McIntire, L. K., McKinley, R. A., Goodyear, C., & Nelson, J. (2014). A Comparison of the Effects of Transcranial Direct Current Stimulation and Caffeine on Vigilance and Cognitive Performance During Extended Wakefulness. *Brain Stimulation*, *7*(4), 499–507. https://doi.org/10.1016/j.brs.2014.04.008

McIntire, L. K., McKinley, R. A., Nelson, J. M., & Goodyear, C. (2017). Transcranial direct current stimulation versus caffeine as a fatigue countermeasure. *Brain Stimulation*, *10*(6), 1070–1078. https://doi.org/10.1016/j.brs.2017.08.005

McLellan, T. M., Caldwell, J. A., & Lieberman, H. R. (2016). A review of caffeine's effects on cognitive, physical and occupational performance. *Neuroscience & Biobehavioral Reviews*, *71*, 294–312. https://doi.org/10.1016/j.neubiorev.2016.09.001

Medina, D., & Barraza, P. (2019). Efficiency of attentional networks in musicians and non-musicians. *Heliyon*, *5*(3), e01315. https://doi.org/10.1016/j.heliyon.2019.e01315

Merritt, P., Hirshman, E., Wharton, W., Stangl, B., Devlin, J., & Lenz, A. (2007). Evidence for gender differences in visual selective attention. *Personality and Individual Differences*, *43*(3), 597–609. https://doi.org/10.1016/j.paid.2007.01.016

Miller, J., Franz, V., & Ulrich, R. (1999). Effects of auditory stimulus intensity on response force in simple, go/no-go, and choice RT tasks. *Perception & Psychophysics*, *61*(1), 107–119. https://doi.org/10.3758/BF03211952

Miquel, S., Haddou, M. Ben, & Day, J. E. L. (2019). A systematic review and meta-analysis of the effects of mastication on sustained attention in healthy adults. *Physiology & Behavior*, *202*(January), 101–115. https://doi.org/10.1016/j.physbeh.2019.01.003

Miró, E., Lupiáñez, J., Hita, E., Martínez, M. P., Sánchez, A. I., & Buela-Casal, G. (2011). Attentional deficits in fibromyalgia and its relationships with pain, emotional distress and sleep dysfunction complaints. *Psychology & Health*, *26*(6), 765–780. https://doi.org/10.1080/08870446.2010.493611

Miró, E., Martínez, M. P., Sánchez, A. I., Prados, G., & Lupiáñez, J. (2014). Men and women with fibromyalgia: Relation between attentional function and clinical symptoms. *British Journal of Health Psychology*, (December 2014), 1–16. https://doi.org/10.1111/bjhp.12128

Morales, J., Padilla, F., Gómez-Ariza, C. J., & Bajo, M. T. (2015). Simultaneous interpretation selectively influences working memory and attentional networks. *Acta Psychologica*, *155*, 82–91. https://doi.org/10.1016/j.actpsy.2014.12.004

Moratal, C., Huertas Olmedo, F., & Lupiáñez, J. (2015). *Efectos de la práctica de ejercicio físico-deportivo sobre las redes atencionales en diferentes grupos de edad (doctoral thesis)*. Universidad Católica de Valencia, Spain.

Moray, N., & Haudegond, S. (1998). An Absence of Vigilance Decrement in a Complex Dynamic Task. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *42*(3), 234–236. https://doi.org/10.1177/154193129804200311

Morgan, K., Johnson, A. J., & Miles, C. (2014). Chewing gum moderates the vigilance decrement. *British Journal of Psychology*, *105*(2), 214–225. https://doi.org/10.1111/bjop.12025

Munafò, M. R., Nosek, B. A., Bishop, D. V. M., Button, K. S., Chambers, C. D., Percie du Sert, N., … Ioannidis, J. P. A. (2017). A manifesto for reproducible science. *Nature Human Behaviour*, *1*(1), 0021. https://doi.org/10.1038/s41562-016-0021

Nelson, J., McKinley, R. A., Phillips, C., McIntire, L., Goodyear, C., Kreiner, A., & Monforton, L. (2016). The Effects of Transcranial Direct Current Stimulation (tDCS) on Multitasking Throughput Capacity. *Frontiers in Human Neuroscience*, *10*(November), 1–13. https://doi.org/10.3389/fnhum.2016.00589

Nelson, J. T., McKinley, R. A., Golob, E. J., Warm, J. S., & Parasuraman, R. (2014). Enhancing vigilance in operators with prefrontal cortex transcranial direct current stimulation (tDCS). *NeuroImage*, *85*, 909–917. https://doi.org/10.1016/j.neuroimage.2012.11.061

Neuhaus, A. H., Urbanek, C., Opgen-Rhein, C., Hahn, E., Ta, T. M. T., Koehler, S., … Dettling, M. (2010). Event-related potentials associated with Attention Network Test. *International*

Journal of Psychophysiology, *76*(2), 72–79. https://doi.org/10.1016/j.ijpsycho.2010.02.005

Niogi, S., Mukherjee, P., Ghajar, J., & McCandliss, B. D. (2010). Individual Differences in Distinct Components of Attention are Linked to Anatomical Variations in Distinct White Matter Tracts. *Frontiers in Neuroanatomy*, *4*(2), 1–12. https://doi.org/10.3389/neuro.05.002.2010

Notebaert, W., Gevers, W., Verbruggen, F., & Liefooghe, B. (2006). Top-down and bottom-up sequential modulations of congruency effects. *Psychonomic Bulletin and Review*, *13*(1), 112–117. https://doi.org/10.3758/BF03193821

Oken, B. S., Salinsky, M. C., & Elsas, S. M. (2006). Vigilances, alertness, or sustained attention: physiological basis and measurement. *Clinical Neurophysiology*, *117*(9), 1885–1901. https://doi.org/10.1016/j.clinph.2006.01.017.

Patton, J. H., Stanford, M. S., & Barratt, E. S. (1995). Factor structure of the barratt impulsiveness scale. *Journal of Clinical Psychology, 51*(6), 768–774. https://doi.org/10.1002/1097-4679(199511)51:6<768::AID-JCLP2270510607>3.0.CO;2-1

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., … Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods*, *51*(1), 195–203. https://doi.org/10.3758/s13428-018-01193-y

Perrier, J., Chavoix, C., & Bocca, M. L. (2015). Functioning of the three attentional networks and vigilance in primary insomnia. *Sleep Medicine*, *16*(12), 1569–1575. https://doi.org/10.1016/j.sleep.2015.06.025

Petersen, A., Petersen, A. H., Bundesen, C., Vangkilde, S., & Habekost, T. (2017). The effect of phasic auditory alerting on visual perception. *Cognition*, *165*, 73–81. https://doi.org/10.1016/j.cognition.2017.04.004

Petersen, S. E., & Posner, M. I. (2012). The Attention System of the Human Brain: 20 Years After. *Annual Review of Neuroscience*, *35*(1), 73–89. https://doi.org/10.1146/annurev-neuro-062111-150525

Pirruccio, V. (2018). *Attentional networks and mindfulness: investigations through multiple indexes (Doctoral dissertation)*. Sapienza Università di Roma. Retrieved from https://iris.uniroma1.it/retrieve/handle/11573/1037839/536391/Tesi dottorato Pirruccio

Pop, V. L., Stearman, E. J., Kazi, S., & Durso, F. T. (2012). Using Engagement to Negate Vigilance Decrements in the NextGen Environment. *International Journal of Human-Computer Interaction*, *28*(2), 99–106. https://doi.org/10.1080/10447318.2012.634759

Posner, M. I. (1980). Orienting of attention. *The Quarterly Journal of Experimental Psychology, 32*(1), 3–25. https://doi.org/10.1080/00335558008248231

Posner, M. I. (2008). Measuring Alertness. *Annals of the New York Academy of Sciences*, *1129*(1), 193–199. https://doi.org/10.1196/annals.1417.011

Posner, M. I. (2012a). Attentional networks and consciousness. *Frontiers in Psychology*, *3*(64), 1–4. https://doi.org/10.3389/fpsyg.2012.00064

Posner, M. I. (2012b). Imaging attention networks. *NeuroImage*, *61*(2), 450–456. https://doi.org/10.1016/j.neuroimage.2011.12.040

Posner, M. I. (2014). Orienting of attention: Then and now. *The Quarterly Journal of Experimental Psychology*, (September), 1–12. https://doi.org/10.1080/17470218.2014.937446

Posner, M. I., & Dehaene, S. (1994). Attentional networks. *Trends in Neurosciences*, *17*(2), 75–79. https://doi.org/10.1016/0166-2236(94)90078-7

Posner, M. I., & Fan, J. (2008). Attention as an Organ System. In J. R. Pomerantz (Ed.), *Topics in Integrative Neuroscience: From Cells to Cognition* (pp. 31–61). Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511541681

Posner, M. I., & Petersen, S. E. (1990). The Attention System of The Human Brain. *Annual Reviews of Neuroscience*, *13*, 25–42. https://doi.org/10.1146/annurev.ne.13.030190.000325

Posner, M. I., Sheese, B. E., Odludaş, Y., & Tang, Y. (2006). Analyzing and shaping human attentional networks. *Neural Networks*, *19*(9), 1422–1429. https://doi.org/10.1016/j.neunet.2006.08.004

Psychology Software Tools, I. (2012). [E-Prime 2.0]. Retrieved from http://www.pstnet.com

Puente-Ontanilla, J. M. (2018). Unpublished data.

R Core Team. (2018). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from https://www.r-project.org

Raichle, M. E. (2015). The Brain's Default Mode Network. *Annual Review of Neuroscience*, (April), 413–427. https://doi.org/10.1146/annurev-neuro-071013-014030

Ralph, B. C. W., Thomson, D. R., Seli, P., Carriere, J. S. A., & Smilek, D. (2015). Media multitasking and behavioral measures of sustained attention. *Attention, Perception, and Psychophysics*, *77*(2), 390–401. https://doi.org/10.3758/s13414-014-0771-7

Reteig, L. C., Talsma, L. J., van Schouwenburg, M. R., & Slagter, H. A. (2017). Transcranial Electrical Stimulation as a Tool to Enhance Attention. *Journal of Cognitive Enhancement*, *1*(1), 10–25. https://doi.org/10.1007/s41465-017-0010-y

Robertson, I. H., Manly, T., Andrade, J., Baddeley, B. T., & Yiend, J. (1997). "Oops!": performance correlates of everyday attentional failures in traumatic brain injured and normal subjects. *Neuropsychologia*, *35*(6), 747–758. https://doi.org/10.1016/S0028-3932(97)00015-8

Roca, J., Castro, C., López-Ramón, M. F., & Lupiáñez, J. (2011). Measuring vigilance while assessing the functioning of the three attentional networks: the ANTI-Vigilance task. *Journal of Neuroscience Methods*, *198*(2), 312–324. https://doi.org/10.1016/j.jneumeth.2011.04.014

Roca, J., Crundall, D., Moreno-Ríos, S., Castro, C., & Lupiáñez, J. (2013). The influence of differences in the functioning of the neurocognitive attentional networks on drivers' performance. *Accident Analysis & Prevention*, *50*, 1193–1206. https://doi.org/10.1016/j.aap.2012.09.032

Roca, J., Fuentes, L. J., Marotta, A., López-Ramón, M.-F., Castro, C., Lupiáñez, J., & Martella, D. (2012). The effects of sleep deprivation on the attentional functions and vigilance. *Acta Psychologica*, *140*(2), 164–176. https://doi.org/10.1016/j.actpsy.2012.03.007

Roca, J., García-Fernández, P., Castro, C., & Lupiáñez, J. (2018). The moderating effects of vigilance on other components of attentional functioning. *Journal of Neuroscience Methods*, *308*, 151–161. https://doi.org/10.1016/j.jneumeth.2018.07.019

Roca, J., Lupiáñez, J., López-Ramón, M.-F., & Castro, C. (2013). Are drivers' attentional lapses associated with the functioning of the neurocognitive attentional networks and with cognitive failure in everyday life? *Transportation Research Part F: Traffic Psychology and Behaviour*, *17*, 98–113. https://doi.org/10.1016/j.trf.2012.10.005

Rocklage, M., Williams, V., Pacheco, J., & Schnyer, D. M. (2009). White Matter Differences Predict Cognitive Vulnerability to Sleep Deprivation. *Sleep*, *32*(8), 1100–1103. https://doi.org/10.1093/sleep/32.8.1100

Rodríguez-Bailón, M., Triviño, M., & Lupiáñez, J. (2012). Executive Attention and Personality Variables in Patients with Frontal Lobe Damage. *The Spanish Journal of Psychology*, *15*(3), 967–977. https://doi.org/10.5209/rev_SJOP.2012.v15.n3.39388

Roe, J. M., Nesheim, M., Mathiesen, N. C., Moberget, T., Alnæs, D., & Sneve, M. H. (2016). The effects of tDCS upon sustained visual attention are dependent on cognitive load. *Neuropsychologia*, *80*, 1–8. https://doi.org/10.1016/j.neuropsychologia.2015.11.005

Rojkova, K., Volle, E., Urbanski, M., Humbert, F., Dell'Acqua, F., & Thiebaut de Schotten, M. (2016). Atlasing the frontal lobe connections and their variability due to age and education: a spherical deconvolution tractography study. *Brain Structure and Function*, *221*(3), 1751–1766. https://doi.org/10.1007/s00429-015-1001-3

Rossi, S., Hallett, M., Rossini, P. M., & Pascual-Leone, A. (2011). Screening questionnaire before TMS: An update. *Clinical Neurophysiology*, *122*(8), 1686. https://doi.org/10.1016/j.clinph.2010.12.037

Roy, L. B., Sparing, R., Fink, G. R., & Hesse, M. D. (2015). Modulation of attention functions by anodal tDCS on right PPC. *Neuropsychologia*, *74*, 96–107. https://doi.org/10.1016/j.neuropsychologia.2015.02.028

Rueda, M. R., Fan, J., McCandliss, B. D., Halparin, J. D., Gruber, D. B., Lercari, L. P., & Posner, M. I. (2004). Development of attentional networks in childhood. *Neuropsychologia*, *42*(8), 1029–1040. https://doi.org/10.1016/j.neuropsychologia.2003.12.012

Ruz, M., & Lupiáñez, J. (2002). A review of attentional capture: On its automaticity and sensitivity to endogenous control. *Psicológica*, *23*, 283–309.

Sadeh, A., Dan, O., & Bar-Haim, Y. (2011). Online assessment of sustained attention following sleep restriction. *Sleep Medicine*, *12*(3), 257–261. https://doi.org/10.1016/j.sleep.2010.02.001

Sakai, H., Uchiyama, Y., Tanaka, S., Sugawara, S. K., & Sadato, N. (2014). Prefrontal transcranial direct current stimulation improves fundamental vehicle control abilities. *Behavioural Brain Research*, *273*, 57–62. https://doi.org/10.1016/j.bbr.2014.07.036

Sanabria, D., Morales, E., Luque, A., Gálvez, G., Huertas, F., & Lupiañez, J. (2011). Effects of acute aerobic exercise on exogenous spatial attention. *Psychology of Sport and Exercise*, *12*(5), 570–574. https://doi.org/10.1016/j.psychsport.2011.04.002

Sanchis, C., Blasco, E., Luna, F. G., & Lupiañez, J. (2019). Effects of caffeine intake and exercise intensity on executive and arousal vigilance. *Manuscript Submitted for*

Publicaction.

Sarter, M., Givens, B., & Bruno, J. P. (2001). The cognitive neuroscience of sustained attention: where top-down meets bottom-up. *Brain Research Reviews*, *35*(2), 146–160. https://doi.org/10.1016/S0165-0173(01)00044-3

Sassenberg, K., & Ditrich, L. (2019). Research in Social Psychology Changed Between 2011 and 2016: Larger Sample Sizes, More Self-Report Measures, and More Online Studies. *Advances in Methods and Practices in Psychological Science*, 251524591983878. https://doi.org/10.1177/2515245919838781

Scerbo, M. W. (1998). 50 Years of Vigilance Research: Where are we now? *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *42*(22), 1575–1579. https://doi.org/10.1177/154193129804202209

See, J. E., Howe, S. R., Warm, J. S., & Dember, W. N. (1995). Meta-analysis of the sensitivity decrement in vigilance. *Psychological Bulletin*, *117*(2), 230–249. https://doi.org/10.1037/0033-2909.117.2.230

See, J. E., Warm, J. S., Dember, W. N., & Howe, S. R. (1997). Vigilance and Signal Detection Theory: An Empirical Evaluation of Five Measures of Response Bias. *Human Factors*, *39*(1), 14–29. https://doi.org/10.1518/001872097778940704

Shallice, T., Stuss, D. T., Alexander, M. P., Picton, T. W., & Derkzen, D. (2008). The multiple dimensions of sustained attention. *Cortex*, *44*(7), 794–805. https://doi.org/10.1016/j.cortex.2007.04.002

Shenhav, A., Botvinick, M. M., & Cohen, J. D. (2013). The expected value of control: an integrative theory of anterior cingulate cortex function. *Neuron*, *79*(2), 217–240. https://doi.org/10.1016/j.neuron.2013.07.007

Shomstein, S. (2012). Cognitive functions of the posterior parietal cortex: top-down and bottom-up attentional control. *Frontiers in Integrative Neuroscience*, *6*(July), 1–7. https://doi.org/10.3389/fnint.2012.00038

Smallwood, J., & Schooler, J. W. (2006). The restless mind. *Psychological Bulletin*, *132*(6), 946–958. https://doi.org/10.1037/0033-2909.132.6.946

Smit, A. S., Eling, P. A. T. M., Hopman, M. T., & Coenen, A. M. L. (2005). Mental and physical effort affect vigilance differently. *International Journal of Psychophysiology*, *57*(3), 211–217. https://doi.org/10.1016/j.ijpsycho.2005.02.001

Smyth, P., Maximova, K., & Jirsch, J. D. (2017). Physicians' attentional performance following a 24-hour observation period: do we need to regulate sleep prior to work? *Occupational and Environmental Medicine*, *74*(8), 553–557. https://doi.org/10.1136/oemed-2015-103489

Soares, J. M., Marques, P., Alves, V., & Sousa, N. (2013). A hitchhiker's guide to diffusion tensor imaging. *Frontiers in Neuroscience*, *7*(March), 31. https://doi.org/10.3389/fnins.2013.00031

Srna, S., Schrift, R. Y., & Zauberman, G. (2018). The Illusion of Multitasking and Its Positive Effect on Performance. *Psychological Science*, *29*(12), 1942–1955. https://doi.org/10.1177/0956797618801013

Stanislaw, H., & Todorov, N. (1999). Calculation of signal detection theory measures.

Behavior Research Methods, Instruments, & Computers : A Journal of the Psychonomic Society, Inc, *31*(1), 137–149. https://doi.org/10.3758/BF03207704

StatSoft, I. (2007). STATISTICA (data analyses software system), version 8.0. Retrieved from www.statsoft.com

Stawarczyk, D., & D'Argembeau, A. (2016). Conjoint influence of mind-wandering and sleepiness on task performance. *Journal of Experimental Psychology: Human Perception and Performance*, *42*(5), 1–53. https://doi.org/10.1037/xhp0000254

Stawarczyk, D., Majerus, S., Maj, M., Van der Linden, M., & D'Argembeau, A. (2011). Mind-wandering: Phenomenology and function as assessed with a novel experience sampling method. *Acta Psychologica*, *136*(3), 370–381. https://doi.org/10.1016/j.actpsy.2011.01.002

Sturm, W., & Willmes, K. (2001). On the Functional Neuroanatomy of Intrinsic and Phasic Alertness. *NeuroImage*, *14*(1), S76–S84. https://doi.org/10.1006/nimg.2001.0839

Takahashi, M., Iwamoto, K., Fukatsu, H., Naganawa, S., Iidaka, T., & Ozaki, N. (2010). White matter microstructure of the cingulum and cerebellar peduncle is related to sustained attention and working memory: a diffusion tensor imaging study. *Neuroscience Letters*, *477*(2), 72–76. https://doi.org/10.1016/j.neulet.2010.04.031

Takao, H., Hayashi, N., & Ohtomo, K. (2011). White matter asymmetry in healthy individuals: a diffusion tensor imaging study using tract-based spatial statistics. *Neuroscience*, *193*, 291–299. https://doi.org/10.1016/j.neuroscience.2011.07.041

Thiebaut de Schotten, M., Dell'Acqua, F., Forkel, S. J., Simmons, A., Vergani, F., Murphy, D. G. M., & Catani, M. (2011). A lateralized brain network for visuospatial attention. *Nature Neuroscience*, *14*(10), 1245–1246. https://doi.org/10.1038/nn.2905

Thomson, D. R., Besner, D., & Smilek, D. (2015). A resource-control account of sustained attention: Evidence from mind wandering and vigilance paradigms. *Perspectives on Psychological Science*, *10*(1), 82–96. https://doi.org/10.1177/1745691614556681

Thomson, D. R., Besner, D., & Smilek, D. (2016). A critical examination of the evidence for sensitivity loss in modern vigilance tasks. *Psychological Review*, *123*(1), 70–83. https://doi.org/10.1037/rev0000021

Thomson, D. R., Seli, P., Besner, D., & Smilek, D. (2014). On the link between mind wandering and task performance over time. *Consciousness and Cognition*, *27*(1), 14–26. https://doi.org/10.1016/j.concog.2014.04.001

Thomson, D. R., Smilek, D., & Besner, D. (2015). Reducing the vigilance decrement: The effects of perceptual variability. *Consciousness and Cognition*, *33*, 386–397. https://doi.org/10.1016/j.concog.2015.02.010

Tkachenko, O., & Dinges, D. F. (2018). Interindividual variability in neurobehavioral response to sleep loss: A comprehensive review. *Neuroscience & Biobehavioral Reviews*, *89*(October 2017), 29–48. https://doi.org/10.1016/j.neubiorev.2018.03.017

Tournier, J.-D., Calamante, F., Gadian, D. G., & Connelly, A. (2004). Direct estimation of the fiber orientation density function from diffusion-weighted MRI data using spherical deconvolution. *NeuroImage*, *23*(3), 1176–1185. https://doi.org/10.1016/j.neuroimage.2004.07.037

Triviño, M., Arnedo, M., Lupiáñez, J., Chirivella, J., & Correa, Á. (2011). Rhythms can overcome temporal orienting deficit after right frontal damage. *Neuropsychologia*, *49*(14), 3917–3930. https://doi.org/10.1016/j.neuropsychologia.2011.10.009

Triviño, M., Correa, Á., Arnedo, M., & Lupiáñez, J. (2010). Temporal orienting deficit after prefrontal damage. *Brain*, *133*(4), 1173–1185. https://doi.org/10.1093/brain/awp346

Wang, R., Benner, T., Sorensen, A. G., & Wedeen, V. J. (2007). Diffusion Toolkit: A Software Package for Diffusion Imaging Data Processing and Tractography. In *15th Annual Meeting of Intl Soc Mag Reson Med* (p. 3720). Berlin.

Warm, J. S., Parasuraman, R., & Matthews, G. (2008). Vigilance Requires Hard Mental Work and Is Stressful. *Human Factors*, *50*(3), 433–441. https://doi.org/10.1518/001872008X312152

Wickens, C. D., Hutchins, S. D., Laux, L., & Sebok, A. (2015). The Impact of Sleep Disruption on Complex Cognitive Tasks. *Human Factors*, *57*(6), 930–946. https://doi.org/10.1177/0018720815571935

Wickham, H. (2011). The Split-Apply-Combine Strategy for Data Analysis. *Journal of Statistical Software*, *40*(1), 1–29. https://doi.org/10.18637/jss.v040.i01

Wiener, E. L., Curry, R. E., & Faustina, M. Lou. (1984). Vigilance and Task Load: In Search of the Inverted U. *Human Factors*, *26*(2), 215–222. https://doi.org/10.1177/001872088402600208

Williams, R. S., Biel, A. L., Wegier, P., Lapp, L. K., Dyson, B. J., & Spaniol, J. (2016). Age differences in the Attention Network Test: Evidence from behavior and event-related potentials. *Brain and Cognition*, *102*, 65–79. https://doi.org/10.1016/j.bandc.2015.12.007

Wixted, J. T. (2019). The forgotten history of signal detection theory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. https://doi.org/10.1037/xlm0000732

Xuan, B., Mackie, M. A., Spagna, A., Wu, T., Tian, Y., Hof, P. R., & Fan, J. (2016). The activation of interactive attentional networks. *NeuroImage*, *129*, 308–319. https://doi.org/10.1016/j.neuroimage.2016.01.017

Yavari, F., Jamil, A., Mosayebi Samani, M., Vidor, L. P., & Nitsche, M. A. (2017). Basic and functional effects of transcranial Electrical Stimulation (tES)—An introduction. *Neuroscience & Biobehavioral Reviews*. https://doi.org/10.1016/j.neubiorev.2017.06.015

Zhou, S., Fan, J., Lee, T. M. C., Wang, C., & Wang, K. (2011). Age-related differences in attentional networks of alerting and executive control in young, middle-aged, and older Chinese adults. *Brain and Cognition*, *75*(2), 205–210. https://doi.org/10.1016/j.bandc.2010.12.003