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Cognitive load mitigates the executive but not the arousal vigilance decrement

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ABSTRACT

Previous research has shown opposite effects of dual tasking on the vigilance decrement phenomenon. We examined the executive (i.e., detecting infrequent critical signals) and arousal (i.e., sustaining a fast reaction to stimuli without much control on responses) vigilance decrements as a function of task load. Ninety-six participants performed either a single signal-detection (i.e., executive vigilance) task, a single reaction time (i.e., arousal vigilance) task, or a dual vigilance task with the same stimuli and procedure. All participants self-reported their fatigue' state along the session. Exploratory analyses included data from a previous study with a triple task condition. Task load significantly modulated the executive but not the arousal vigilance decrement. Interestingly, the largest increase in mental fatigue was observed in the single executive vigilance task condition. We discuss limitations of classic vigilance theories to account for the vigilance decrement and changes in mental fatigue as a function of task load.

1. Introduction

The vigilance decrement phenomenon is usually observed in simple and monotonous behavioral tasks (Hancock, 2017; Thomson et al., 2016), such as the Mackworth Clock Test (MCT; Mackworth, 1948), the Sustained Attention to Response Task (SART; Robertson et al., 1997), or the Psychomotor Vigilance Test (PVT; Lim & Dinges, 2008). Although vigilance is typically assessed in single task conditions, there has been nevertheless considerable interest in examining whether the cognitive load of the task modulates vigilance (Hancock & Matthews, 2019; Helton & Russell, 2017; Thomson et al., 2015). Importantly, evidence reported so far seems to be inconsistent, supporting either detrimental (Epling et al., 2016; Helton & Russell, 2011) or rather null (Epling et al., 2019; Moray & Haudegond, 1998; Stearman & Durso, 2016) effects of task load on vigilance.

Classic vigilance tasks as the MCT (Mackworth, 1948) and the SART (Robertson et al., 1997) require monitoring and detecting infrequent critical signals (i.e., targets) across time-on-task. Whereas in the MCT a specific response is only executed on targets

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(Mackworth, 1948), in the SART instead the response, continuously executed on frequent non-target (i.e., noise) stimuli, must be inhibited when a target is detected (Helton, 2009; Robertson et al., 1997). In such signal-detection tasks, the vigilance decrement is observed as a drop in hits (i.e., correct target's detection), which has been mainly attributed to a loss in sensitivity to correctly discriminate signal among noise stimuli (Jun et al., 2019; See et al., 1995). In the past few years, however, the sensitivity loss observed in signal-detection tasks has been criticized (Claypoole et al., 2018; Neigel et al., 2019; Thomson et al., 2016). In short, Thomson et al. (2016) objected that in single signal-detection tasks there is usually a floor rate in false alarms (FA) that could be masking a change in response bias. Indeed, recent research has demonstrated that when FA are not at floor, the decrement corresponds to an increase in response bias towards a conservative criterion rather than to a loss in sensitivity (Claypoole et al., 2018; Luna, Barttfeld, et al., 2021; Thomson et al., 2016).

Nowadays, one of the most accepted accounts concerning the vigilance decrement is the resource depletion model (Esterman & Rothlein, 2019; Fortenbaugh et al., 2017; Neigel et al., 2020; Thomson et al., 2015, 2016). Based on the assumptions that vigilance tasks are difficult to perform, demand hard mental work, and are subjectively experienced as unpleasant (Dillard et al., 2019), the resource depletion model posits that the vigilance decrement would be due to a progressive loss of the available attentional resources across time-on-task (R. A. Grier et al., 2003; Warm et al., 2008). Importantly, impaired vigilance was found in dual tasking (e.g., simultaneously performing the SART and a memory task, see Head & Helton, 2014) in contrast to single task situations (e.g., just performing the SART), being these outcomes interpreted as evidence supporting the resource depletion hypothesis (Chua et al., 2017; Epling et al., 2016; Head & Helton, 2014; Helton & Russell, 2011; Smit et al., 2004). In particular, the resource depletion model predicts that the higher the task load, the larger the attentional resources imposed by the tasks at hand and therefore, the larger the vigilance decrement (R. A. Grier et al., 2003; Warm et al., 2008).

Nevertheless, and contrary to the predictions of the resource depletion hypothesis, opposite effects were observed in other studies, in which dual tasking did not lead to a larger vigilance decrement (Epling et al., 2019) or even mitigated it (Moray & Haudegond, 1998; Stearman & Durso, 2016). This set of outcomes received considerable interest in ergonomics and applied research, as disentangling the particular conditions in which concurrent task load mitigates the vigilance decrement might help to prevent attentional failures in modern work environments (Hancock & Matthews, 2019; Helton & Russell, 2017; Neigel et al., 2020). In this vein, based on a meta-analysis of four experiments, Stearman & Durso (2016) proposed dissociable effects of the type of cognitive load of the task: whereas in dual tasking vigilance did not decrease across time-on-task, it was impaired when task instructions were quite complex. An alternative approach regarding the negative effects of cognitive underload over vigilance was proposed by the malleable attentional resources theory (Young & Stanton, 2002). From this account, the size of attentional resources' pool is not fixed but dependent on the demands imposed by the external task at hand. Therefore, in less demanding tasks there would be a reduced recruitment of attentional resources, which leads to important vigilance decrements. In contrast, by making more demanding the task the size of the attentional resources' pool would increase, thus explaining the mitigation of the vigilance decrement of even the positive effects of cognitive load on vigilance performance (Young & Stanton, 2002).

Note that, at difference with signal-detection tasks (Mackworth, 1948; Robertson et al., 1997), there are other single reaction time (RT) tasks as the PVT wherein vigilance is rather measured as the capacity to sustain a fast reaction to a single stimulus (e.g., stopping as fast as possible a millisecond counter in the PVT; Lim & Dinges, 2008). Importantly, in the PVT, stimuli are not categorized as signal and noise, as the same stimulus is always presented, and therefore participants do not need to select among different response options, only having to press any available key to stop the counter (Basner & Dinges, 2011). In the PVT, the vigilance decrement is observed as an increase in mean and variability of RT, and lapses (e.g., RT slower than 500 ms) across time-on-task (Basner & Dinges, 2011; Kiss & Linnell, 2020; Lim & Dinges, 2008). Importantly, Buckley et al. (2016) observed detrimental effects of dual tasking in vigilance in the PVT, as the decrement in mean RT and lapses was larger than in single task condition. However, some contradictory outcomes were found, as increasing the cognitive load (i.e., simultaneously performing a driving and subtraction task) prior to the PVT after a night of sleep deprivation mitigated the proportion of lapses, showing therefore beneficial effects of cognitive load in vigilance (Rupp et al., 2004). It is important to note that one potential problem with all these studies is that different task environments are used in single and dual task conditions, either in signal-detection or RT vigilance tasks.

Aiming at dissociating the decrement in signal-detection (Mackworth, 1948; Robertson et al., 1997) and RT (Lim & Dinges, 2008) vigilance tasks, we have recently developed the Attentional Networks Test for Interactions and Vigilance – executive and arousal components (ANTI-Vea; Luna et al., 2018). The ANTI-Vea is a triple cognitive task combining: (a) the Attentional Networks Test for Interactions (ANTI) of Callejas et al. (2004) to assess the classic attentional networks' components, (b) a signal-detection subtask similar to the MCT (Mackworth, 1948), and (c) a RT subtask that mimics the PVT (Lim & Dinges, 2008). Importantly, note that there is a long-standing discussion concerning whether the concept of vigilance either defines the ability to sustain attention as a single dimension, with different tasks like the MCT or the PVT being different tasks to measure the same process, or rather refer to dissociable components, with the different tasks measuring different behavioral and physiological mechanisms for sustaining attention during long periods (Langner & Eickhoff, 2013; Oken et al., 2006; Sarter et al., 2001; Shallice et al., 2008; Sturm & Willmes, 2001; van Schie et al., 2021). By simultaneously measuring vigilance with two clearly different paradigms, we have developed a line of research showing that vigilance can be indeed understood as two dissociated components (Luna et al., 2018). In the ANTI-Vea, whereas the signal-detection subtask assesses the executive component of vigilance (EV) as a control mechanism to monitor and detect critical signals by executing specific responses to them, the PVT subtask rather measures the arousal component of vigilance (AV), usually associated with changes in the sleep-wake cycle (Basner & Dinges, 2011; Lim & Dinges, 2008), as the maintenance of arousal to quickly react to any stimuli without implementing much control on responses (Oken et al., 2006).

Notably, the EV and AV decrements are both successfully and simultaneously observed with the ANTI-Vea (Luna et al., 2018; Luna, Barttfeld, et al., 2021; Luna, Roca, et al., 2021): the EV decrement as a linear drop in the percentage of hits and an increase in response

bias, similarly to recent findings in single signal-detection tasks (Claypoole et al., 2018; Thomson et al., 2016), and the AV decrement as a linear increase in mean and variability of RT, and lapses, as usually observed with the PVT (Buckley et al., 2016; Kiss & Linnell, 2020; Lim & Dinges, 2008). Most importantly, recent research has shown dissociable effects on EV and AV. While anodal transcranial direct current stimulation over the fronto-parietal network (Luna et al., 2020) and moderate exercise intensity (Sanchis et al., 2020) only mitigated the EV decrement, caffeine ingestion only showed beneficial effects on AV across time-on-task (Sanchis et al., 2020), and accumulated fatigue after 6 h of performing cognitive tasks specifically impaired AV (Feltmate et al., 2020). Moreover, recent research has shown positive effects of sport practice and age in young children (Huertas et al., 2019) and musical practice in healthy adults (Román-Caballero et al., 2020) in both EV and AV components. Altogether, this set of recent outcomes might have potential applications in future research, as determining the particular conditions in which the decrement in each vigilance component is mitigated might help to understand the underlying mechanisms of EV/AV as well as developing future applied programs for preventing vigilance failures and attentional lapses.

1.1. The present study

Noting that vigilance components are usually measured independently in signal-detection tasks as the MCT (i.e., EV) or RT tasks as the PVT (i.e., AV) and that dual tasking showed contradictory effects on both EV (Epling et al., 2016, 2019; Helton & Russell, 2011; Stearman & Durso, 2016) and AV (Buckley et al., 2016; Rupp et al., 2004), the present study aimed at further analyzing the modulation of cognitive load over the EV and the AV decrement. To this end, vigilance components were assessed in single or dual task conditions with the ANTI-Vea, wherein the EV and AV decrement were already observed at the same experimental session (Luna et al., 2018; Luna, Barttfeld, et al., 2021; Luna, Roca, et al., 2021). Importantly, as the ANTI-Vea combines three tasks, this design allows us to manipulate cognitive load within the same paradigm and stimulation, therefore solving the methodological problems of previous studies. Thus, following the same procedure, ANTI-Vea task's instructions were manipulated to assess: (a) EV in single signal-detection tasks as the MCT (Mackworth, 1948) or the SART (Robertson et al., 1997), (b) AV in single RT task as the PVT (Lim & Dinges, 2008), and (c) EV and AV in dual task condition.

Following the resources depletion hypothesis, the cognitive load imposed in dual tasking would lead to a greater depletion of attentional resources and therefore to a larger EV (Epling et al., 2016; Helton & Russell, 2011; Warm et al., 2008) and AV (Buckley et al., 2016) decrement than in single tasks. However, there might be other factors of dual tasking that might prevent a larger decrement in dual than in single task, as the increase in the arousal level (Rupp et al., 2004) or motivation (Srna et al., 2018) by performing multiple tasks can improve performance when dual task's instructions can be easily assimilated to simultaneously complete two tasks (Stearman & Durso, 2016). Lastly, to more deeply examine the modulation of task load on the EV/AV decrement, data of the present study and from a previous one (Luna, Barttfeld, et al., 2021) –wherein vigilance components were measured in a triple task condition (i.e., completing the standard ANTI-Vea)– were jointly analyzed in a series of exploratory analyses. Importantly, these exploratory analyses also addressed the assumption that single vigilance tasks demand hard mental work and are subjectively perceived as unpleasant (Dillard et al., 2019; Warm et al., 2008) by examining the mental and physical fatigue state self-reported across the session in both the present study and Luna, Barttfeld, et al. (2021). Altogether, the present research seeks to further clarify the detrimental or rather beneficial effects of task load on vigilance components.

2. Material and methods

2.1. Participants

Ninety-six 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 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 Universidad de Granada Ethical Committee (175/CEIH/2017).

Participants were assigned by counter-balance selection to one of four groups as a function of the task performed. Groups did not differ in age or education years (both $Fs < 1$). Sample size was estimated based on prior research using the ANTI-Vea task (i.e., considering the same sample size by group as in Experiment 1 of Luna et al., 2018), and data were analyzed only after collecting data from all participants, without using any stopping rule. Using G*Power 3.1.9.4 (Faul et al., 2007), sensitivity analysis show that with 24 participants by group and six within-participant measures (i.e., experimental blocks), the minimum effect size of a within-between interaction that could have been detected for $\alpha = .05$ and $1 - \beta = .80$ is $\eta_p^2 = .05$, for both an interaction between three groups (i.e., EV decrement) and between two groups (i.e., AV decrement), which is indeed smaller than the effect size observed for the within-between interaction for hits in EV ($\eta_p^2 = .06$) and for mean RT in AV ($\eta_p^2 = .07$).

2.2. Procedure and design

2.2.1. Self-report questionnaires

Prior to the experimental task, participants completed the Insomnia Severity Index (Bastien et al., 2001), the Cognitive Failures Questionnaire (Broadbent et al., 1982), the Attentional Control Scale (Derryberry & Reed, 2002), and the Barratt Impulsiveness Scale-

11 (Patton et al., 1995). The goal of collecting these data is to correlate several self-reported measures with attentional and vigilance performance' scores. However, this goal is part of a larger project and therefore these data will be reported elsewhere when data from a much larger *N* is accumulated.

2.2.2. Mental and physical fatigue

Participants self-reported their mental and physical fatigue state at three different times along the session: baseline (i.e., before the instructions and practice), pre-task (i.e., before starting the experimental blocks), and post-task (i.e., at the end of the session). The order in which mental and physical fatigue was assessed was counterbalanced across participants although fixed for the three different times for a given participant. Additionally –and counterbalanced across participants– one fatigue type was reported in a numeric scale (from 1 –minimum– to 9 –maximum–) following the method and structure of the Karolinska Sleepiness Scale (Åkerstedt & Gillberg, 1990) and the other type by an analog scale (a visual line from the left –minimum– to right –maximum– of the screen) as in the visual analog scale method (Cline et al., 1992). Given that either numeric or visual analog scales are usually administered to assess fatigue (Gawron, 2016), mental and physical fatigue were assessed with different scales to better differentiate between the two, a goal that is also part of a larger project. Although no reliability measures have been reported for these scales to date (Gawron, 2016), the Karolinska Sleepiness Scale has been proposed as a valid self-reported measure of sleepiness, given the positive correlation observed between the self-reported scores and electroencephalographic signals of sleepiness (Kaida et al., 2006). Regarding the use of the visual analog scale with a single item (i.e., as in the present study), previous research has shown positive correlation between self-reported scores in this scale and lapses in the PVT (Chua et al., 2012) as well as a correspondence between self-reported scores of fatigue and the vigilance decrement observed at the neural level when performing a single signal-detection task (Boksem et al., 2005).

In the present study, data from the analog scale were converted into a numeric scale to analyze the two fatigue types independently of the scale. We aimed at examining whether changes in mental and physical fatigue across time-on-task are modulated by task load. Therefore, fatigue scores from the single/dual tasks of the present study are reported together with data gathered in another experiment (Luna, Barttfeld, et al., 2021) wherein EV and AV were measured in a triple task (i.e., the standard ANTI-Vea) in the section number 5.

2.2.3. Vigilance tasks

The experimental tasks were designed and run in E-Prime v2.0 Professional (Psychology Software Tools, 2012). All stimuli and instructions were drawn in black against a grey background. Responses were registered with a standard QWERTY keyboard. Participants sat at ~ 50 cm from the screen, which had a resolution in pixels (px) of 1024 wide and 768 height.

Each group of participants received the same stimuli procedure and timing of the standard ANTI-Vea of Luna et al. (2018; see Fig. 1) but, importantly, with particular instructions to perform the two vigilance tasks or just one of them (see Fig. 2 below). The ANTI-Vea comprises three types of trial: (a) noise trials of the embedded signal-detection subtask (60%, i.e., the usual ANTI trials, in which the target appears not displaced from the surrounding distractors), (b) EV signal trials of the embedded signal-detection subtask (20%, in which the target is vertically displaced from distractors), and (c) AV trials (20%, a subtask similar to the PVT). In the standard ANTI-Vea, the noise trials (i.e., ANTI trials) also serve as a flankers' paradigm with auditory and visual cues to assess the classic attentional networks functions (Luna et al., 2018). Importantly, in the present study, participants never had to complete the noise trials as the flanker subtask by responding to the direction the central arrow pointed to as in the standard ANTI-Vea (Luna et al., 2018). However,

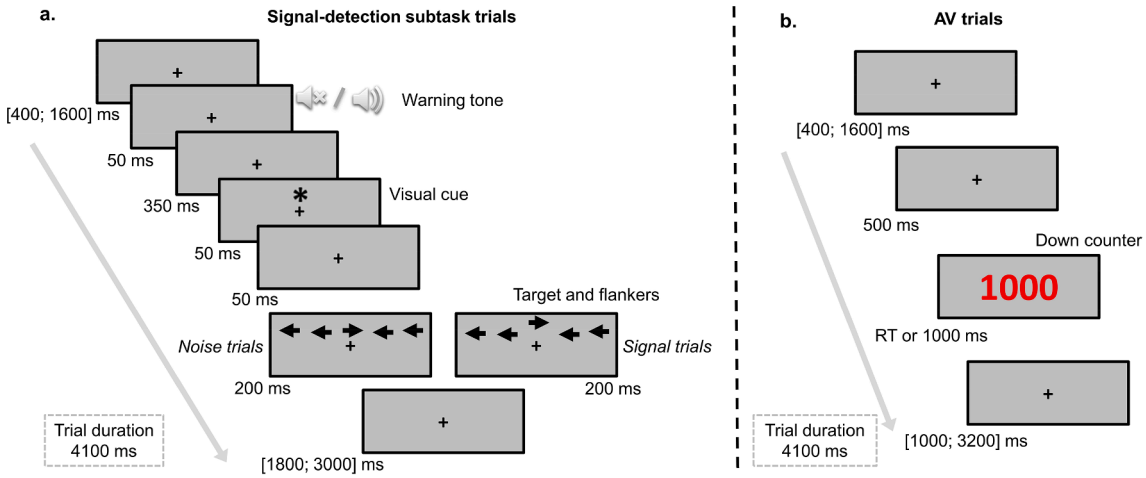

Fig. 1. Stimuli Timing and Procedure for (a) Signal-detection Subtask Trials and (b) AV Trials. *Note.* In all trials, responses were allowed until 2000 ms since the response' stimuli appearance. The initial and final fixation point had a random timing so that all trials lasted 4100 ms, although temporal uncertainty about target appearance was maintained. In panel (b), the number 1000 represents the millisecond down counter stimuli for AV trials. The down counter started at 1000 and descended until 0 or until it was stopped by pressing the space bar key (although any key was available for stopping the down counter, as in the standard ANTI-Vea).

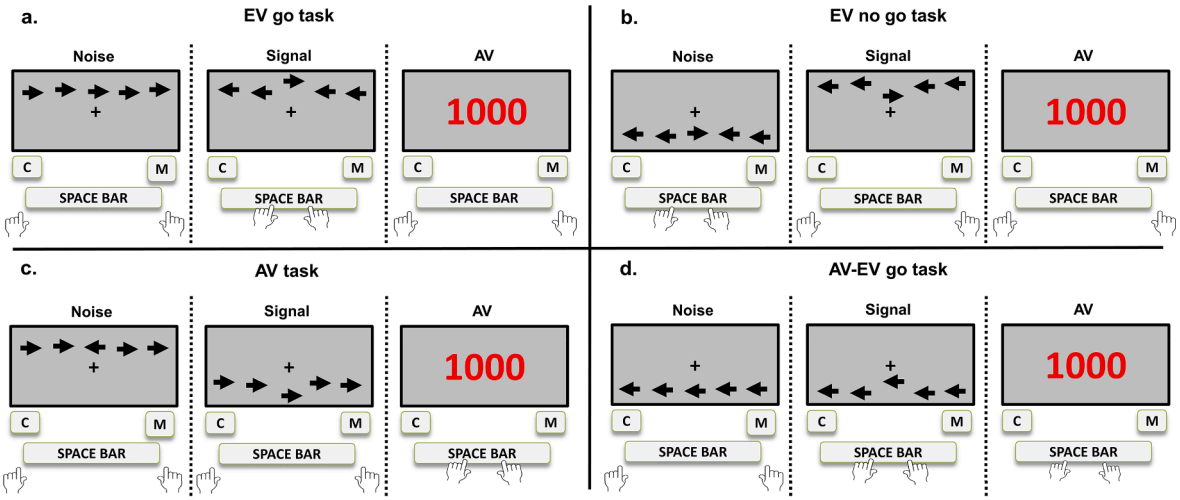

Fig. 2. Correct Responses and Representative Examples for each type of Trial as a function of the Experimental Task performed. *Note*. In the standard ANTI-Vea, 'C' and 'M' are correct responses for the embedded flanker subtask, which was not to be completed in the present study. In both the noise and signal trials, the string of arrows could appear above or below the fixation point, and the target and flankers could point either leftwards or rightwards. In the noise trials the central target was aligned with the flanking arrows, whereas in the signal trials it was largely displaced either above or below the string of flanking arrows. In the screens depicted for the AV trials, the number 1000 represents the millisecond down counter stimuli for that type of trial.

we decided to present all trials and stimuli exactly as in the standard ANTI-Vea, to examine the vigilance decrement as a function of cognitive load but maintaining the same stimuli, environment, and trials structure. The stimuli procedure for all trials is depicted in Fig. 1 and described in detail in Luna et al. (2018).

Participants completed the ANTI-Vea just performing either the signal-detection subtask –suitable to assess EV as in the MCT or the SART–, the AV subtask –suitable to assess AV as in the PVT–, or both vigilance tasks simultaneously. To assess the EV component, participants were instructed to remain vigilant to detect an infrequent vertical large displacement of the target (i.e., the central arrow of a horizontal string of five arrows) from its central position (see Fig. 1, panel a), which only occurred in the signal trials. To make more difficult the detection of the infrequent displacement, in the noise trials a random variability of ± 2 px was set for the horizontal and vertical position of the target and flankers. Instead, in the signal trials, the displacement of the target was larger and fixed (i.e., 8 px either upwards or downwards). To assess the AV component, in the AV trials a down counter was presented as the response' stimuli (see Fig. 1, panel b) and participants were instructed to stop it as fast as possible. Note that the AV trials had the same stimuli timing than the noise and signal ones, but no auditory or visual cue was presented, as in the PVT.

As above-mentioned, in the present study each group of participants received particular instructions to perform either only the EV subtask, the AV subtask, or both vigilance tasks simultaneously. Thus, the only difference between the vigilance tasks of this experiment was the correct response expected for each trial, as explained below and depicted in Fig. 2.

2.2.3.1. Executive vigilance - go for signal task (EV go). This task was similar to the MCT (Mackworth, 1948), wherein a single response was executed to the infrequent stimuli (i.e., signal) and inhibited to the frequent ones (i.e., noise). As participants were only instructed to complete the signal-detection subtask while ignoring the AV trials, this task aimed at measuring the EV component in single task conditions. Therefore, in the signal trials the correct answer was to press the space bar, whereas in the noise trials no key should be pressed (see Fig. 2, panel a). A first practice block of 32 randomized trials (16 noise and 16 signal) with visual feedback was given. Next, participants were told that sometimes a millisecond counter could appear (i.e., AV trials) and a visual example was given. In these trials, the correct answer was to wait until the counter finished, without pressing any key. Then, a second practice block of 48 randomized trials (16 noise, 16 signal, and 16 AV), also with visual feedback, was completed. Lastly, a final practice block without visual feedback with 24 noise, 8 signal, and 8 AV trials, i.e., half of one experimental block, was completed.

The experimental section of the task comprised six blocks of 80 randomly presented trials (48 noise, 16 signal, and 16 AV) without any pause or feedback, i.e., 32 min 48 sec of vigilance period.

2.2.3.2. Executive vigilance - no go for signal task (EV no go). Contrary to the EV go task, in this group the signal-detection subtask was similar to the SART (Robertson et al., 1997). This task also aimed at measuring the EV component in signal task conditions as the EV go task, as participants were only instructed to complete the signal-detection subtask while ignoring the AV trials. The critical difference between this task and the EV go task was the expected response to the signal/noise trials, although both tasks instructions specified that the infrequent critical target in the signal trials had to be detected. Note that Robertson et al. (1997) proposed in the SART a modified response pattern to single signal-detection tasks as the MCT (Mackworth, 1948), by requiring participants to continuously execute a single response to noise stimuli while inhibiting it to signal ones. This continuously executed response to noise stimuli was expected to

help achieving higher levels of attentional engagement than when response is only executed to infrequent targets (Robertson et al., 1997). Thus, in the present study, to assess EV component as proposed in the SART (Robertson et al., 1997), the correct answer was to continuously press the space bar in the noise trials, whereas in the signal trials no key should be pressed (neither in the AV trials, as no response was required also for the counter in this task; see Fig. 2, panel b). Practice blocks structure as well as the experimental section of the task were the same as in the EV go task above-detailed.

2.2.3.3. Arousal vigilance task (AV). Participants only completed the AV trials, thus performing a single RT task as the PVT (Lim & Dinges, 2008). Contrary to EV go and EV no go tasks, which aimed at measuring the EV component in a single signal-detection task, this AV task aimed at measuring the AV component in single task condition. To this end, participants kept in mind one single instruction while performing the task, i.e., to respond to the AV trials while ignoring in all cases the noise and signal trials of the embedded signal-detection subtask. Thus, whenever the millisecond counter was presented, the space bar should be pressed as fast as possible (although all keys were allowed to be pressed, as in the standard ANTI-Vea). A first practice block with visual feedback including only 16 AV trials was completed. Next, it was mentioned that sometimes a row of five arrows could appear and no key should be pressed in these trials (i.e., both noise and signal; see Fig. 2, panel c). After that, a second practice block with visual feedback was given, including 48 randomized trials (16 noise, 16 signal, and 16 AV). Participants then completed a final practice block without visual feedback with 24 noise, 8 signal, and 8 AV trials, i.e., half of one experimental block.

Importantly, the experimental section of the task was the same as in the other groups, including six blocks of 80 randomly presented trials (48 noise, 16 signal, and 16 AV) without any pause or feedback, i.e., 32 min 48 sec of vigilance period.

2.2.3.4. Arousal and executive (go for signal) vigilance task (AV – EV go). In the dual task group, participants simultaneously completed the signal-detection (as the EV go for signal task) and the AV subtask. Importantly, this dual task aimed at increasing cognitive load in contrast to the single signal-detection (i.e., EV go and EV no go) and single AV tasks above-described, as in the current task participants had to keep in mind two instructions all time to simultaneously complete two vigilance tasks in a single session. We decided to design the dual vigilance task by maintaining the same responses expected to the signal and AV trials as in the standard ANTI-Vea, to therefore compare the vigilance decrements in this dual task condition with that observed in the triple task condition (i.e., measured in the standard ANTI-Vea, see section 5). Therefore, in the current dual vigilance task, for both signal and AV trials, the space bar was to be pressed as correct response, whereas no key was to be pressed for the noise trials (see Fig. 2, panel d). First, instructions to correctly complete the EV go task were given, followed by a practice block of 32 randomized trials (16 noise and 16 signal) with visual feedback. Next, instructions for the AV task were presented, with a second practice block of 48 randomized trials (16 noise, 16 signal, and 16 AV), with visual feedback. As in the other groups, a final practice block without visual feedback with 24 noise, 8 signal, and 8 AV trials, i.e., half of one experimental block, was completed.

The experimental section of the task was the same as in the other groups, including six blocks of 80 randomly presented trials (48 noise, 16 signal, and 16 AV) without any pause or feedback, i.e., 32 min 48 sec of vigilance period.

2.3. Data analyses

Analyses were performed in RStudio v.1.3.1073 (R Core Team, 2020; RStudio Team, 2020) and data figures were made with Matplotlib 3.0.0 (Hunter, 2007). Three participants were excluded from analyses: two participants due to poor performance (i.e., ~50% of hits or FA) and another one due to technical issues (i.e., responses were collected only in the first block). Final groups were conformed as follows: EV go ($n = 23$), EV no go ($n = 22$), AV ($n = 24$), and AV – EV go ($n = 24$).

To analyze the vigilance decrement across time-on-task, EV and AV measures were obtained per experimental block. Using the afex package (Singmann et al., 2020) in RStudio, mixed Analysis of Variance (ANOVA) were conducted as follows. For EV, hits were computed as the proportion of infrequent signals (i.e., the 8 px displaced targets) correctly detected. Importantly, to avoid a possible floor effect in FA that could masks a potential change in response bias (Thomson et al., 2016), FA were computed following the method developed by Luna, Barttfeld, et al. (2021) to analyze the standard ANTI-Vea, i.e., considering only those noise trials wherein there was a 3 or 4 px of vertical distance between the target and one of the most adjacent distractors. Next, non-parametric indices of sensitivity (A') and response bias (B″) were computed (J. B. Grier, 1971; Stanislaw & Todorov, 1999). Note that non-parametric indices of signal-detection theory are distribution free, so they can be computed without transforming the data when hits are 100% and FA are 0% (i.e., which are scores usually observed in vigilance tasks when performance is analyzed by blocks) to fit scores into a normal distribution, as it is necessary for computing parametric indices of sensitivity (i.e., *d*') and response bias (i.e., β) (Stanislaw & Todorov, 1999). Then, four mixed ANOVAs were separately conducted including block (6 levels) as within-participant factor and task version (EV go/EV no go/AV-EV go) as between-participants factor, one for each dependent variable: hits, FA, A' and B″.

The AV decrement was analyzed with mean and *SD* of RT, and the percentage of lapses as dependent variables per block. Following Luna et al. (2018), lapses were computed as responses slower than 600 ms. Then, three mixed ANOVAs were separately conducted, including block (6 levels) as within-participant factor and task version (AV/AV-EV go) as between-participants factor, one for each dependent variable.

All ANOVAs are reported with partial eta-squared (η_p^2) as measure of the effect size (Kelley & Preacher, 2012) and 95% confidence intervals around them (Cumming, 2014). When the sphericity assumption was violated (i.e., Mauchly's test $p < .05$), degrees of freedom are reported with Greenhouse-Geisser correction. Importantly, for both EV and AV analyses, using the emmeans package (Lenth, 2020) in RStudio, planned comparisons of the polynomial linear component across blocks were performed to determine

statistical differences of the decrement between groups. Effect sizes for planned comparisons were computed with the effect size package (Ben-Shachar et al., 2020) in RStudio. To account for statistical significance in planned comparisons, all contrasts' p values were adjusted by Hommel correction (Hommel, 1988).

3. Results

3.1. Executive vigilance decrement

3.1.1. Hits

The main effect of task version was observed as significant for hits [F (2, 66) = 3.23, p = .046, η_p^2 = .09, 95% CI (.00, .23)]. Planned comparisons determined that overall hits were higher [t (66) = 2.47, p = .032, η_p^2 = .08, 95% CI (.00, .23)] in the dual (AV – EV go M = 93.52%, 95% CI [90.64, 96.39]) than in the two single tasks (EV go M = 89.84%, [86.94, 92.73]; EV no go M = 88.51%, [85.60, 91.44]), which did not differ significantly from each other [t (66) = -0.64, p = .527, η_p^2 < .01, (.00, .09)]. Importantly, as depicted in Fig. 3, a significant decrement in hits across blocks was observed [F (4.16, 274.61) = 6.97, p < .001, η_p^2 = .10, (.04, .15)], with a significant linear component [t (330) = −5.37, p < .001, η_p^2 = .08, (.03, .14)], that was significantly modulated by task version [F (8.32, 274.61) = 2.18, p = .027, η_p^2 = .06, (.00, .09)]. Planed comparisons demonstrated a significant linear component for the two single tasks [EV go and EV no go: t (330) = −6.44, p < .001, η_p^2 = .11, (.06, .18)], that was not significant for the dual task [AV – EV go: t (330) = −0.10, p = .943, η_p^2 < .01, (.00, .01)]. Importantly, the linear decrement was significantly different when the two single tasks were compared together against the dual task [t (330) = 3.72, p = .004, η_p^2 = .04, (.01, .09)].

3.1.2. False alarms

The main effect of task version was not significant for FA [F (2, 66) = 1.52, p = .227, η_p^2 = .04, (.00, .16)]. Overall FA were similar for all tasks (EV go: M = 13.30%, [8.17, 18.43]; EV no go: M = 15.27%, [10.10, 20.44]; AV – EV go: M = 19.43%, [14.33, 24.53]). Importantly, as observed in Fig. 3, there was not a significant main effect of blocks [F (4.35, 287.22) = 2.00, p = .089, η_p^2 = .03, (.00, .06)] nor a significant modulation of task version over blocks [F (8.70, 287.22) = 0.78, p = .627, η_p^2 = .02, (.00, .04)] for FA. Planned comparisons determined that no task version showed a significant different linear change in FA when it was contrasted with the other tasks: EV go vs. EV no go [t (330) = −0.76, p = .897, η_p^2 < .01, (.00, .02)], EV go vs. AV – EV go [t (330) = −1.11, p = .897, η_p^2 < .01, (.00, .03)], and EV no go vs. AV – EV go [t (330) = −0.33, p = .897, η_p^2 < .01, (.00, .01)].

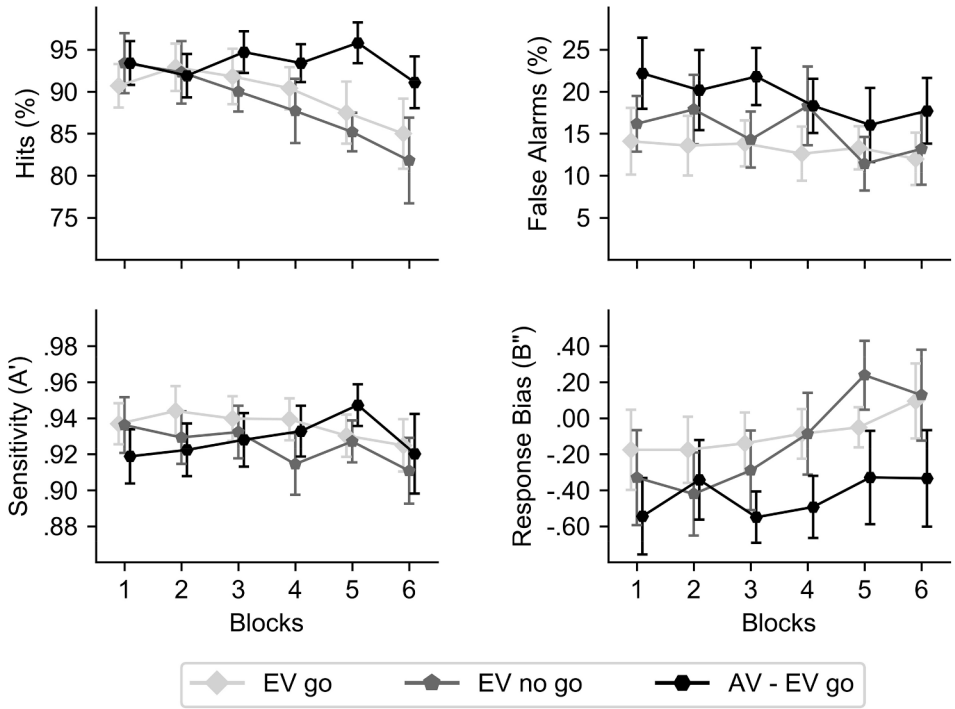

Fig. 3. Executive vigilance performance across time on task. *Note.* Hits (superior left graph), false alarms (superior right graph), sensitivity (inferior left graph), and response bias (inferior right graph). Error bars represent 95% confidence intervals and were computed following the method developed by Cousineau (2005).

3.1.3. Sensitivity

The main effect of task version was not significant for A' [F (2, 66) = 0.60, p = .553, η_p^2 = .02, (.00, .10)]: overall A' was similar in all tasks (EV go: A' = .94, [.92, .95]; EV no go: A' = .93, [.91, .94]; and AV – EV go: A' = .93, [.91, .94]). As observed in the same Fig. 3, A' did not show a significant main effect of blocks [F (4.32, 285.88) = 1.68, p = .150, η_p^2 = .03, (.00, .05)], neither a significant modulation of blocks by the task version [F (8.64, 285.88) = 1.39, p = .196, η_p^2 = .04, (.00, .08)].

3.1.4. Response bias

The main effect of task version was marginal for B″ [F (2, 66) = 3.07, p = .053, η_p^2 = .09, (.00, .22)]. Planned comparisons determined [t (66) = −2.46, p = .032, η_p^2 = .08, (.00, .23)] that the dual task (AV – EV go: B″ = −.43, [−.65, −.22]) showed the most liberal response bias compared to the two single tasks (EV go: B″ = −.09, [−.31, .12]; EV no go: B″ = −.13, [−.35, .09]). Importantly, as depicted in the same Fig. 3, B″ showed a significant increment across blocks [F (4.28, 282.46) = 4.91, p < .001, η_p^2 = .07, (.02, .12)] with a significant linear component [t (330) = 4.61, p < .001, η_p^2 = .06, (.02, .12)], that did not show a significant interaction with task version [F (8.56, 282.46) = 1.34, p = .221, η_p^2 = .04, (.00, .06)]. Nevertheless, given our hypotheses and to further inspect the pattern observed in Fig. 3, planned comparisons determined that while the two single tasks showed a significant linear increase in B″ [t (330) = 4.72, p < .001, η_p^2 = .06, (.02, .12)], this increase was not significant in the dual task [t (330) = 1.27, p = .972, η_p^2 < .01, (.00, .03)].

3.2. Arousal vigilance decrement

3.2.1. Mean RT

As depicted in Fig. 4, a significant main effect of task version was observed for mean RT [F (1, 46) = 13.23, p < .001, η_p^2 = .22, (.05, .42)]. The overall RT was higher in the dual (AV – EV go: M = 446 ms, [425, 468]) than in the single (AV: M = 391 ms, [370, 413]) task. Importantly, a significant main effect of blocks [F (3.83, 176.39) = 4.64, p = .002, η_p^2 = .09, (.02, .15)] with a significant linear component [t (230) = 4.46, p < .001] for mean RT was found, which was significantly modulated by task version [F (3.83, 176.39) = 3.29, p = .014, η_p^2 = .07, (.01, .12)]. Planned comparisons showed that while in the single task there was a clear linear increase in mean RT across blocks [t (230) = 5.79, p < .001, η_p^2 = .13, (.06, .21)], in the dual task the linear component was not significant [t (230) = 0.52, p = .987, η_p^2 < .01, (.00, .03)]. Importantly, the linear components of these task versions were significantly different from each other [t (230) = 3.72, p = .003, η_p^2 = .06, (.01, .12)].

3.2.2. Variability of RT

The *SD* of RT showed a significant increase across blocks [F (3.67, 169.00) = 3.79, p = .007, η_p^2 = .08, (.01, .13)] with a significant linear component [t (230) = 4.03, p < .001, η_p^2 = .07, (.02, .14)]. However, in contrast to mean RT, the modulation of task version over blocks for variability of RT was not significant [F (3.67, 169.00) = 0.25, p = .898, η_p^2 < .01, (.00, .01)] (see also Fig. 4). Planned comparisons showed a significant linear component in the dual [t (230) = 3.06, p = .038, η_p^2 = .04, (.00, .10)] that did not reach significance in the single [t (230) = 2.64, p = .124, η_p^2 = .03, (.00, .08)] task. Importantly, however, the comparison between the linear components of the single and dual tasks was not significant [t (230) = -0.29, p = .993, η_p^2 < .01, (.00, .02)]. In addition, the main effect of task version was clearly not significant [F (1, 46) = 0.25, p = .616, η_p^2 < .01, (.00, .11)]. The single (AV: *SD* = 74, [60, 88]) and the dual (AV – EV go: *SD* = 79, [65, 94]) task showed similar overall *SD* of RT.

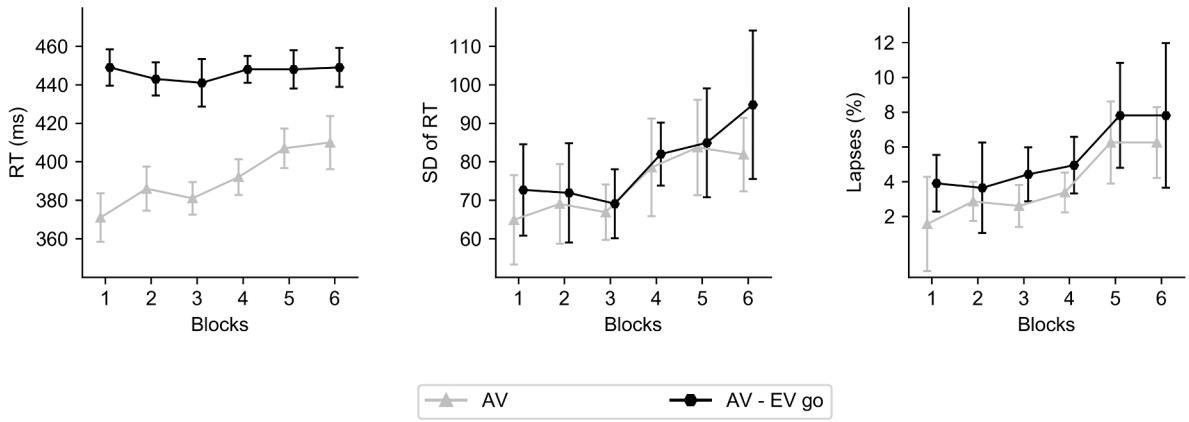

Fig. 4. Arousal vigilance performance across time on task. *Note*. Mean RT (left graph), SD of RT (center graph), and lapses percentage (right graph). Error bars represent 95% confidence intervals and were computed following the method developed by Cousineau (2005).

3.2.3. Lapses percentage

As observed in the same Fig. 4, lapses also significantly increased across blocks [F (3.08, 141.81) = 5.11, p = .002, η_p^2 = .10, (.03, .16)] with a significant linear component [t (230) = 4.70, p < .001, η_p^2 = .09, (.00, .16)]. However, task version modulation over blocks was not significant for lapses [F (3.08, 141.81) = 0.09, p = .969, η_p^2 < .01, (.00, .00)]. Planned comparisons demonstrated that lapses linearly increased for both the single [t (230) = 3.41, p = .010, η_p^2 = .05, (.01, .11)] and the dual task [t (230) = 3.23, p = .019, η_p^2 = .04, (.01, .11)], and that the comparison between these linear components was not significant [t (230) = 0.13, p = .898, η_p^2 < .01, (.00, .01)]. Similarly, the main effect of task version was far from significance [F (1, 46) = 0.67, p = .416, η_p^2 = .01, (.00, .14)]. Overall lapses were similar for the single (AV: M = 3.82%, [1.03, 6.61]) and the dual (AV – EV go: M = 5.43%, [2.64, 8.21]) task.

4. Discussion

The present experiment demonstrated that the cognitive load of the task (i.e., single vs. dual) differently modulated vigilance components. In particular, regarding EV, the percentage of hits rate was higher and the response criterion was more liberal in the dual than in the single EV tasks. Most important, while in the dual task both the percentage of hits and the response bias showed no significant change across time-on-task, in the two single EV tasks a linear decrease in hits, as well as an increase towards a more conservative response criterion, were observed. Regarding AV, mean RT showed a linear increase only in the single AV task but not in the dual task, although the AV decrement was independent of task load in the variability of RT and lapses across time-on-task. Note that, interestingly, overall mean RT in the AV component was slower in the dual task than in the single task condition, an outcome that might fit well with resource depletion theory (Warm et al., 2008). However, although overall performance in mean RT was impaired by dual tasking, mean RT did not change across time-on-task in the dual task condition but it did increase in the single AV task, conversely to the predictions stated by the resource depletion model.

Altogether, the outcomes of the present experiment seem to be inconsistent with previous evidence supporting that higher levels of cognitive load lead to a larger depletion of attentional resources and therefore to a larger vigilance decrement (Epling et al., 2016; Head & Helton, 2014; Helton & Russell, 2011). One possible explanation for this set of outcomes might be provided by the malleable resources attentional theory (Young & Stanton, 2002). In this vein, it might be possible that the size of the attentional resources' pool would be reduced in the single task condition but increased in the dual task one, thus mitigating the vigilance decrement in the AV – EV go task (except for RT variability in the AV component, which was independent of the cognitive load). Thus, to further examine the modulation of the cognitive load of the task on the EV/AV decrement and the changes in mental/physical fatigue across time-on-task, a series of exploratory analyses are presented in the following section, jointly analyzing data gathered in single/dual tasks of the present study and a triple task condition completed in a separated study (Luna, Barttfeld, et al., 2021).

5. Exploratory analyses across studies

Aiming at more deeply examining the modulation of task load on vigilance components and on the self-reported state of fatigue across time-on-task, in this section, we present a series of exploratory analyses that jointly analyze data gathered from two separated studies. In particular, (a) the present study, wherein participants performed either a single EV/AV task or a dual vigilance task; and (b) the study of Luna, Barttfeld, et al. (2021), wherein participants performed a triple cognitive task (i.e., the standard ANTI-Vea). The experimental procedure of the standard ANTI-Vea was briefly described in section 2.2.3, as the single/dual vigilance tasks of the present study were designed following the general procedure of the standard ANTI-Vea. It is important to note that instructions to complete the standard ANTI-Vea demand a triple cognitive task, thus measuring multiple attentional and vigilance functions at the same time. To this end, the noise trials of the signal-detection subtask serve a double purpose: (a) on the one hand, as in these trials the target is never vertically displaced, the expected response to the infrequent critical signal (i.e., the space bar key) was never to be pressed (otherwise, the response was computed as a FA); and (b) on the other hand, in these trials participants must complete the ANTI task of Callejas et al. (2004), which combines a flanker paradigm with auditory and visual cues for measuring the classic attentional networks components. Thus, in the standard ANTI-Vea completed in Luna, Barttfeld, et al. (2021), participants kept in mind three instructions all time to perform three embedded subtasks that are randomly presented, in particular: (a) a flanker subtask that follows the procedure of the ANTI task (Callejas et al., 2004), suitable for measuring the independence and interactions of phasic alertness, orienting, and executive control; (b) a signal-detection subtask, suitable for measuring the EV decrement as in the MCT; and (c) a reaction time subtask, suitable for measuring the AV decrement as in the PVT.

Importantly, in the present exploratory analyses, cognitive load was manipulated while maintaining constant all other variables, as single, dual, and triple task conditions were conducted with the same stimuli, timing, procedure, and task environment. Thus, EV and AV scores were computed from the same proportion of trials with the same procedure and timing in all cognitive load conditions. Note that, in the following exploratory analyses, as non-significant differences in the decrement and overall performance between the two single EV tasks' groups of the present study were observed, we decided to collapse both groups into a single one (n = 45). Therefore, the cognitive load was categorized as between-participant factor with final groups conformed as follows: EV single task (n = 45), AV single task (n = 24), dual task (i.e., AV – EV go, n = 24), and triple task (i.e., standard ANTI-Vea of Luna et al., 2021, n = 40). To account for sample size differences in groups, exploratory analyses were conducted with Linear Mixed-Effects (LME) models in RStudio (R Core Team, 2020; RStudio Team, 2020) with the lme4 (Bates et al., 2015) and lmerTest (Kuznetsova et al., 2017) packages. All analyses included task load and time-on-task as fixed effects and participants as random effect. LME models were fitted using restricted

maximum likelihood and degrees of freedom were computed using Sattherthwaite's method. Effect sizes for post-hoc comparisons were computed with the effect size package (Ben-Shachar et al., 2020).

5.1. Executive and arousal vigilance decrement as a function of the cognitive load

For each vigilance component, we analyzed the most sensitive score to describe the decrement in performance across time-on-task, in particular: (a) hits for EV and (b) the variability (i.e., *SD*) of RT for AV. Then, hits and *SD* of RT were analyzed as dependent variables in two separated LME models, with blocks (6 levels) and task load (EV or AV single/dual/triple) as fixed effects. Post-hoc comparisons analyzed overall differences and the polynomial linear component across blocks as a function of task load.

For the EV component (see Fig. 5), a significant drop in hits across blocks [F (5, 530) = 6.19, $p < .001$, $\eta_p^2 = .06$, (.02, .09)] along with a significant main effect of task load [F (2, 106) = 14.03, $p < .001$, $\eta_p^2 = .21$, (.08, .33)] was observed. Interestingly, post-hoc comparisons determined that the highest hit rate was observed in the dual task (M = 93.45%, [89.80, 97.09]), in comparison with the single EV (M = 89.12%, [86.46, 91.78]) and the triple (M = 81.77%, [78.95, 84.60]) task, [t (106) = 3.84, $p < .001$, $\eta_p^2 = .12$, (.03, .24)]. The modulation of task load over the decrement in hits was observed, although did not reach statistical significance [F (10, 530) = 1.79, $p = .060$, $\eta_p^2 = .03$, (.00, .06)]. However, as observed in Fig. 5, post-hoc comparisons showed that the non-change in hits observed in the dual task was significantly different to the linear decrement observed in both the EV single [t (530) = 3.15, $p = .005$, $\eta_p^2 = .02$, (.00, .05)] and the triple task [t (530) = 2.84, $p = .013$, $\eta_p^2 = .02$, (.00, .04)]. Interestingly, although overall performance was better for the EV single than the triple task, the comparison between these task's linear decrements was not significant [t (530) = -0.29, $p = .956$, $\eta_p^2 < .01$, (.00, .01)].

In contrast, the AV decrement (see Fig. 5) demonstrated a significant increment in *SD* of RT across blocks [F (5, 425) = 4.14, $p = .001$, $\eta_p^2 = .05$, (.01, .08)] with a significant linear component [t (425) = 2.76, $p = .006$, $\eta_p^2 = .02$, (.00, .05)] that, importantly, clearly did not show a significant modulation by task load [F (10, 425) = 0.38, $p = .954$, $\eta_p^2 < .01$, (.00, .00)]. In addition, the main effect of task load was far from significance [F (2, 85) = 0.20, $p = .820$, $\eta_p^2 < .01$, (.00, .05)]. Thus, following these exploratory analyses of data gathered from separated studies, it seems that cognitive load modulates particularly the EV but not the AV decrement.

5.2. Mental and physical fatigue as a function of the cognitive load

To jointly analyze the scores reported with the numeric and the analog scales used to assess fatigue (see the 2.2.2 section), first, we transformed data collected with the analog method into a numeric score. Specifically, the visual line of the analog method was off-line divided into nine equal segments (i.e., the same number of available options in the numeric scale). Thus, for instance, if a participant clicked in the visual line within the fourth segment, the rate of fatigue was transformed to a score equal to four. Note that this transformation was necessary to have self-reported states of both mental and physical fatigue in a similar score for all participants.

Then, mental and physical fatigue were analyzed as dependent variables in two separated LME models, with the session period (baseline/pre-task/post-task) and task load (EV single/AV single/dual/triple) as fixed effects. Post-hoc comparisons analyzed the changes between baseline and pre-task periods, and between pre and post-task periods, as a function of task load.

As expected, both the mental [F (2, 258) = 110.88, $p < .001$, $\eta_p^2 = .46$, (.38, .53)] and the physical [F (2, 258) = 96.02, $p < .001$, $\eta_p^2 = .43$, (.34, .50)] fatigue state increased across the session period (see Table 1). However, and importantly, task load only modulated changes in mental fatigue [F (6, 258) = 3.21, $p = .005$, $\eta_p^2 = .07$, (.01, .12)], whereas this modulation was far from significance for physical fatigue [F (6, 258) = 1.02, $p = .415$, $\eta_p^2 = .02$, (.00, .05)].

Post-hoc comparisons with the single EV group as the contrast condition showed no significant differences between groups in the

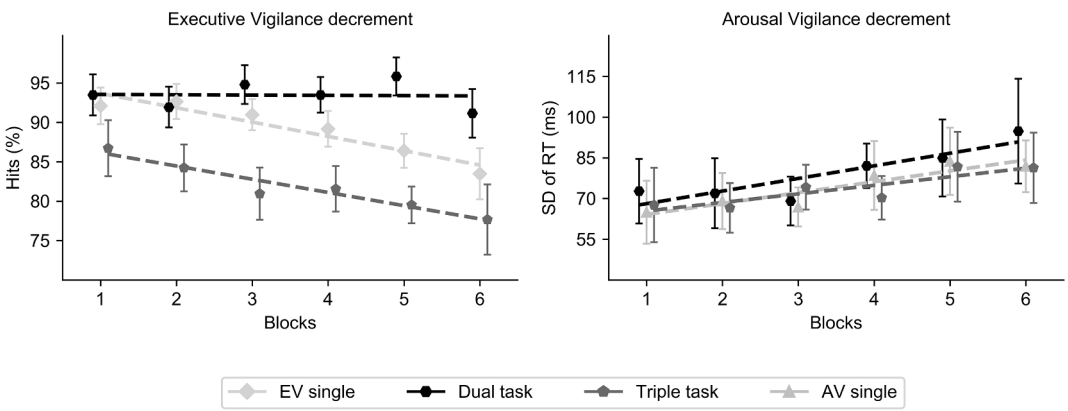

Fig. 5. Executive and arousal vigilance decrement as a function of the cognitive load of the task. *Note*. The segmented lines represent the linear component of each task. Error bars represent 95% confidence intervals and were computed following the method developed by Cousineau (2005).

change from baseline to pre-task period neither in the mental {[EV single vs. AV single: [t (258) = −0.86, p = .389, η_p^2 < .01, (.00, .03)]; EV single vs. dual: [t (258) = −0.01, p = .995, η_p^2 < .01, (.00, .00)]; EV single vs. triple: [t (258) = −1.56, p = .121, η_p^2 < .01, (.00, .05)]} nor in the physical {[EV single vs. AV single: [t (258) = −1.40, p = .163, η_p^2 < .01, (.00, .04)]; EV single vs. dual: [t (258) = −0.58, p = .564, η_p^2 < .01, (.00, .02)]; EV single vs. triple: [t (258) = 1.95, p = .052, η_p^2 = .01, (.00, .06)]} fatigue state. However, and importantly, clear differences were observed afterwards between mental and physical fatigue. For mental fatigue, the increase between pre and post-task periods in the EV single group was significantly larger than the increase observed in the triple [t (258) = 2.52, p = .012, η_p^2 = .02, (.00, .07)] and the dual [t (258) = 2.05, p = .041, η_p^2 = .02, (.00, .06)] task group, but was not significantly different from that observed in the single AV group [t (258) = 1.76, p = .078, η_p^2 = .01, (.00, .05)]. In contrast, the change in the physical fatigue state from pre-task to post-task period was not significantly different for the EV single group in comparison to the triple [t (258) = 0.40, p = .690, η_p^2 < .01, (.00, .02)], the dual [t (258) = 0.83, p = .401, η_p^2 < .01, (.00, .03)], and the single AV [t (258) = 0.23, p = .821, η_p^2 < .01, (.00, .02)] task group.

Finally, post-hoc comparisons between the AV single group in contrast with the dual and the triple task group did not show significant changes neither in the mental fatigue state from baseline to pre-task period {[AV single vs. dual: [t (258) = 0.75, p = .454, η_p^2 < .01, (.00, .03)]; AV single vs. triple: [t (258) = −0.46, p = .642, η_p^2 < .01, (.00, .02)]} or from pre-task to post-task period {[AV single vs. dual: [t (258) = 0.25, p = .803, η_p^2 < .01, (.00, .02)]; AV single vs. triple: [t (258) = 0.39, p = .696, η_p^2 < .01, (.00, .02)]}, nor in the physical fatigue state from baseline to pre-task period {[AV single vs. dual: [t (258) = 0.72, p = .473, η_p^2 < .01, (.00, .03)]; AV single vs. triple: [t (258) = −0.27, p = .783, η_p^2 < .01, (.00, .02)]} or from pre-task to post-task period {[AV single vs. dual: [t (258) = −0.92, p = .357, η_p^2 < .01, (.00, .03)]; AV single vs. triple: [t (258) = 0.11, p = .909, η_p^2 < .01, (.00, .01)]}. Therefore, in summary, as depicted in Fig. 6, the EV single task seems to be the one wherein it was found the most prominent increase in mental (and not physical) fatigue across the session.

6. General discussion

The present study aimed at further examining the modulation of cognitive load on the vigilance decrement, a phenomenon traditionally studied by simple and monotonous tasks (Hancock, 2017; Thomson et al., 2016). To this end, vigilance components were examined in single, dual, and triple task conditions. Importantly, while EV was analyzed as the ability to detect critical signals (Mackworth, 1948; Robertson et al., 1997), AV was measured as the capacity to sustain a fast reaction to stimuli without much control across time-on-task (Lim & Dinges, 2008). To better dissociate the modulation of cognitive load on vigilance components, we used the ANTI-Vea, a triple task wherein the EV and AV decrement are simultaneously observed (Luna et al., 2018; Luna, Barttfeld, et al., 2021; Luna, Roca, et al., 2021) and have been dissociated at the physiological (Sanchis et al., 2020) and neural (Luna et al., 2020) levels. Finally, exploratory analyses jointly analyzed data from the present study and a previous one (Luna, Barttfeld, et al., 2021), examining the EV/AV decrement and the mental/physical fatigue state across time-on-task in single/dual/triple task conditions.

Regarding EV, the decrement in hits was observed in the single EV tasks but mitigated in the dual task, conversely with previous outcomes wherein increasing the cognitive load impaired vigilance in signal-detection tasks (Chua et al., 2017; Epling et al., 2016; Head & Helton, 2014; Helton & Russell, 2011; Smit et al., 2004). In line with previous research, in the single EV tasks sensitivity showed no change across time-on-task and the decrement in hits rather corresponded to a linear increase in response bias (Claypoole et al., 2018; Thomson et al., 2016). Importantly, the increase in response bias was mitigated in the dual as compared to the single task, showing therefore beneficial effects of cognitive load on EV across time-on-task (Epling et al., 2019; Moray & Haudegond, 1998; Stearman & Durso, 2016).

For the AV component, the linear increase in mean RT was observed only in the single but not in the dual task, again showing some beneficial effects of cognitive load on the vigilance decrement (Rupp et al., 2004). However, task load did not modulate the linear increase in variability of RT or percentage of lapses across time-on-task. Importantly, the change in variability of RT has been proposed as evidence of two different vigilance states: 'in the zone', wherein a stable performance and fewer errors are observed, or 'out of the zone', wherein variability increases and therefore it is more likely that attentional lapses occur (Esterman et al., 2013; Fortenbaugh

Table 1
Mental and physical fatigue state across the session as a function of the cognitive load of the task.

	EV single *M* [95% CI]	AV single *M* [95% CI]	Dual task *M* [95% CI]	Triple task *M* [95% CI]
Mental fatigue				
Baseline	3.71 [3.20, 4.22]	4.12 [3.43, 4.82]	3.96 [3.26, 4.66]	3.45 [2.91, 3.99]
Pre-task	4.42 [3.91, 4.93]	4.46 [3.76, 5.16]	4.67 [3.97, 5.37]	3.58 [3.03, 4.12]
Post-task	6.82 [6.31, 7.33]	6.08 [5.38, 6.78]	6.17 [5.47, 6.87]	5.03 [4.48, 5.57]
Physical fatigue				
Baseline	3.67 [3.11, 4.23]	4.12 [3.36, 4.89]	3.96 [3.19, 4.72]	3.42 [2.83, 4.02]
Pre-task	4.29 [3.73, 4.85]	4.25 [3.48, 5.02]	4.38 [3.61, 5.14]	3.45 [2.86, 4.04]
Post-task	5.67 [5.11, 6.23]	5.71 [4.94, 6.47]	5.46 [4.69, 6.22]	4.95 [4.36, 5.54]

Note: *M* = mean; CI = confidence intervals; EV = executive vigilance; AV = arousal vigilance.

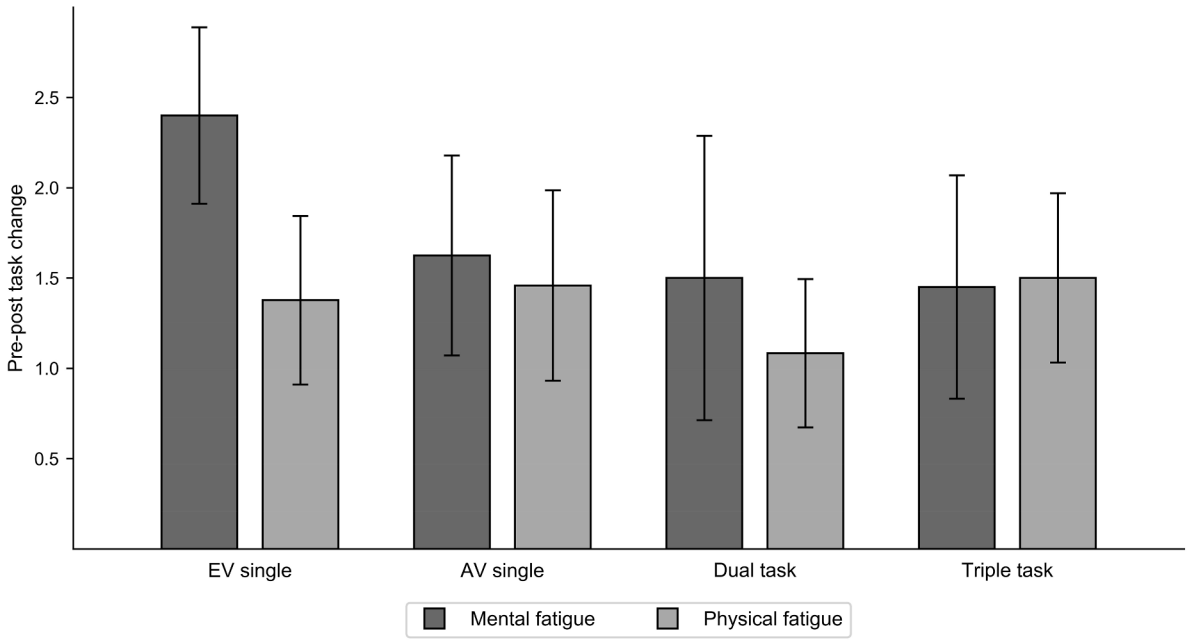

Fig. 6. Mean difference of mental and physical fatigue change between pre-task and post-task periods. *Note*. Error bars represent 95% confidence intervals of means.

et al., 2015). From this perspective, it could be possible that AV would be more independent of task load than EV, and mean RT is a less pure measure of AV than RT variability. Mean RT, even in simple RT task might have some executive component related to response preparation and voluntary temporal orienting (Triviño et al., 2010). Further studies are, however, required to better clarify this issue.

Interestingly, exploratory analyses showed the highest level of performance in an intermediate level of workload (i.e., dual tasking), as anticipated by the inverted-U function hypothesis (Wiener et al., 1984). However, this optimal level in dual tasking might depend on the nature of task demands and/or the cognitive processes imposed by the external tasks, rather than on just the number of tasks being simultaneously performed (Stearman & Durso, 2016). Note that, in a previous study (i.e., Experiment 1 of Luna et al., 2018) wherein participants completed a dual task (i.e., the ANTI-Vigilance task, which combines a signal-detection and a flanker task) different from the current one, both a drop in hits and an increase in response bias were observed, in contrast with the present outcomes. Moreover, while in the current dual task participants reached an overall ~ 93% of hits, in that ANTI-Vigilance overall hits was quite smaller, i.e., ~62% (Luna et al., 2018). Nevertheless, although exploratory analyses showed that cognitive load particularly modulated the EV but not the AV decrement, to confirm these findings future studies should examine the EV and AV components in single/dual/triple task conditions by randomly assigning participants to experimental groups.

Considering all these outcomes together, it seems imperative to review whether the most accepted theoretical frameworks concerning the vigilance decrement are adequate to anticipate modulations of this phenomenon by cognitive load. The resource depletion model (R. A. Grier et al., 2003; Warm et al., 2008) cannot explain why the EV decrement was observed in the single but not in the dual task, neither why participants experienced the greatest mental fatigue in the single EV tasks than in the dual or triple task condition. An alternative framework to the resource depletion hypothesis was proposed in the past decades, known as the mind-wandering account, which posits that resources are re-directed –rather than depleted– to internal irrelevant thoughts unnecessary to perform the task at hand (Smallwood, 2010). From this alternative model, simple vigilance tasks are perceived as boring and monotonous by participants and therefore increasing task engagement might mitigate the decrement across time-on-task (Danckert & Merrifield, 2016; Thomson et al., 2015). Whereas in the present study the non-change in hits in the dual task might be explained as an increase in task engagement –in contrast with the decrement observed in single tasks–, this reasoning however presents limitations in explaining the decrement in the triple task in contrast with the stable performance in the dual task.

In the past few years, the resource-control model was proposed as a new integrative framework for vigilance decrement (Thomson et al., 2015). This model posits that the amount of attentional resources is permanent and initially distributed by executive control between the external task and mind-wandering. As time-on-task progresses, however, executive control declines, thus failing both to avoid the emergence of task-irrelevant thoughts and to sustain attention on the external activity (Thomson et al., 2015). We consider that this framework fits well with the outcomes observed here in the single tasks, wherein the low cognitive load and the monotonous nature of the task lead to both a decrement in hits and the greatest mental fatigue state. In the dual task condition, cognitive control would sustain an optimal allocation of resources, thus reducing 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 mental fatigue change in the dual compared to the single task condition. In the triple task condition, instead, the complex nature of the ANTI-Vea task would force the distribution of attentional resources between the main and secondary

tasks rather than between the single external task and internal irrelevant thoughts, as it seems to occur in simple tasks (Danckert & Merrifield, 2016; Thomson et al., 2015). Thus, in a complex task, performance costs could be observed as a small decrement in all subtasks, whereas in a single signal-detection task mind-wandering would demand a great amount of attentional resources, thus causing a large vigilance decrement.

Nevertheless, although the loss of cognitive control in high-demanding tasks might be considered as a critical fact supporting the resource-control model proposed by Thomson et al. (2015), further studies are required to better develop appropriate theoretical accounts to explain the vigilance decrement phenomenon as a function of cognitive load. Future research should investigate more deeply the nature of mind-wandering thoughts as a function of cognitive load as well as further factors accounting for the intrinsic relationship between executive control and mind-wandering. In this vein, recent theoretical reviews suggest that mind-wandering should be conceived as an heterogeneous construct comprising multiple kinds of mind-wandering thoughts (Seli et al., 2018) and, importantly, mind-wandering measures must take this taxonomy into account to appropriately identify the particular type of thoughts occurring while the external task is being completed (Murray et al., 2020). Indeed, it has been observed that the relationship between mind-wandering and executive control performance is moderated by the content and context of mind-wandering episodes as well as by the daydreaming' style reported by participants (Marcusson-Clavertz et al., 2016).

As stated in a recent theoretical review, it seems that neither the classical (i.e., resource overload and mind-wandering) nor other alternative theories of vigilance (based on arousal states, the influence of rewards on performance, or resource-control) can fully explain the plethora of results reported in cognitive, clinical, and neuroscience research concerning the vigilance decrement (Esterman & Rothlein, 2019). Thus, future research should consider the integration of classic, alternative, and/or novel models of vigilance, along with the development of new methodological approaches, to further understand the fluctuations of vigilance across time-on-task in diverse cognitive load conditions.

7. Conclusions

To conclude, the present study demonstrates that cognitive load particularly modulates the EV but not the AV decrement. Importantly, whereas a linear decrement in hits was observed in the single and triple task conditions, no decrement was observed in the dual task, as predicted by the inverted-U function hypothesis (Wiener et al., 1984). In modern work environments, dual tasking or increased task demands (Young & Stanton, 2002) might have beneficial rather than detrimental effects on vigilance across time-on-task when tasks instructions can be easily assimilated (Stearman & Durso, 2016). Future studies are required to develop theoretical frameworks suitable to account for the vigilance decrement under diverse cognitive load situations (Neigel et al., 2020).

Data statement

The methods, analysis, and datasets analyzed during the current study are available in the Open Science Framework repository, https://osf.io/wnfdv/.

CRediT authorship contribution statement

Fernando G. Luna: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Pablo Barttfeld:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – review & editing, Supervision. **Elisa Martín-Arévalo:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing – review & editing, Visualization, Supervision. **Juan Lupiáñez:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Preliminary results of this work has been presented in the Spanish XI Scientific Meeting of Attention (RECA), developed from 28th to 30th of September 2017 in Baeza, Spain. This study is part of the doctoral thesis by FGL, conducted under the supervision of JL and EMA.

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