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Event-related potentials associated with attentional networks evidence changes in executive and arousal vigilance

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Abstract

Attention is regulated by three independent but interacting networks, that is, alerting, comprising phasic alertness and vigilance, orienting, and executive control. Previous studies analyzing event-related potentials (ERPs) associated with attentional networks have focused on phasic alertness, orienting, and executive control, without an independent measure of vigilance. ERPs associated with vigilance have been instead measured in separate studies and via different tasks. The present study aimed to differentiate ERPs associated with attentional networks by simultaneously measuring vigilance along with phasic alertness, orienting, and executive control. Forty participants (34 women, age: M = 25.96; SD = 4.96) completed two sessions wherein the electroencephalogram was recorded while they completed the Attentional Networks Test for Interactions and Vigilance—executive and arousal components, a task that measures phasic alertness, orienting, and executive control along with executive (i.e., detection of infrequent critical signals) and arousal (i.e., sustaining a fast reaction to environmental stimuli) vigilance. ERPs previously associated with attentional networks were replicated here: (a) N1, P2, and contingent negative variation for phasic alertness; (b) P1, N1, and P3 for orienting; and (c) N2 and slow positivity for executive control. Importantly, different ERPs were associated with vigilance: while the executive vigilance decrement was associated with an increase in P3 and slow positivity across time-on-task, arousal vigilance loss was associated with reduced N1 and P2 amplitude. The present study shows that attentional networks can be described by different ERPs simultaneously observed in a single session, including independent measures of executive and arousal vigilance on its assessment.

1 | INTRODUCTION

Attentional networks (i.e., alerting, which comprises phasic alertness and vigilance, orienting, and executive control) detect, select, and organize internal and external information received to adapt our behavior to the environment (Petersen & Posner, 2012; Posner & Dehaene, 1994; Posner & Petersen, 1990). To differentiate the neural mechanisms underlying attentional networks (Posner, 2012; Posner et al., 2006; Raz & Buhle, 2006), there has been considerable interest in examining event-related potentials (ERPs) associated with each of the three attentional networks (Abundis-Gutiérrez et al., 2014; Galvao-Carmona et al., 2014; Gonçalves et al., 2018; Neuhaus et al., 2010; Zani & Proverbio, 2017; Zhang et al., 2018). While most of these studies have focused on ERPs associated with phasic alertness, orienting, and executive control, ERPs associated with vigilance have been studied in relative isolation and via different behavioral tasks. In particular, vigilance has been measured either via signal-detection (Boksem et al., 2005; Reteig et al., 2019) or single reaction time (RT) (Hoedlmoser et al., 2011; Ramautar et al., 2013; Witkowski et al., 2015) tasks. In the present study, we integrated different methodological approaches used in previous research to simultaneously assess phasic alertness, orienting, executive control, and vigilance (Abundis-Gutiérrez et al., 2014; Lara et al., 2018; Ramautar et al., 2013) to, therefore, differentiate changes in ERPs associated with attentional networks within a single session.

Attentional networks-associated ERPs have been previously examined using the attentional networks test (ANT) (Galvao-Carmona et al., 2014; Gonçalves et al., 2018; Neuhaus et al., 2010; Zani & Proverbio, 2017; Zhang et al., 2018) or its variation for additionally measuring the interactions among the networks (ANTI) (Abundis-Gutiérrez et al., 2014). In short, these tasks present warning signals and visual spatial cues—to assess phasic alertness and orienting, respectively—which might precede the target of a flanker paradigm, thus measuring executive control (Callejas et al., 2004; Fan et al., 2002). The orienting network is underlaid by subcortical regions, as the superior colliculus and the pulvinar nuclei of the thalamus, and cortical areas, as the frontal eye fields and the posterior parietal cortex (Fan et al., 2005; Posner, 2016). ERPs associated with this network suggests that visual spatial cues modulate P1 and N1 in occipital regions for early target detection (Galvao-Carmona et al., 2014; Gonçalves et al., 2018; Neuhaus et al., 2010). Interestingly, Abundis-Gutiérrez et al. (2014) also observed that P3 amplitude increases in central parietal regions when invalid spatial cues reorient target localization in contrast to valid cues.

The executive control network is supported by the anterior cingulate and the dorsolateral prefrontal cortex (Botvinick et al., 2004; Fan et al., 2005; Shenhav et al., 2013). Changes in late ERPs have been associated with executive control (Abundis-Gutiérrez et al., 2014; Gonçalves et al., 2018; Neuhaus et al., 2010; Zani & Proverbio, 2017). Some studies reported that P3 modulates distractor inhibition at parietal (Gonçalves et al., 2018) and also frontal (Neuhaus et al., 2010) central regions. Within this network, Abundis-Gutiérrez et al. (2014) dissociated two mechanisms: conflict detection is associated with N2 at central-frontal regions, while conflict resolution seems to be associated with a late amplitude decrease (i.e., the so-called slow positivity potential, SP) at central and parietal areas. Importantly, previous research has also examined modulations of phasic alertness and orienting on the executive control network (Abundis-Gutiérrez et al., 2014; Zani & Proverbio, 2017). While in Abundis-Gutiérrez et al. no modulation of phasic alertness or orienting over N2 and SP was observed, in Zani and Proverbio (2017) the SP was earlier in the predictive spatial cue condition, showing some benefits of orienting on conflict resolution.

The alerting network regulates both phasic alertness and vigilance, and is supported by connections from the locus coeruleus to parietal and prefrontal cortices (Fan et al., 2005; Posner, 2008). Research on the alerting network in which attentional networks tasks were used has mainly assessed phasic alertness, that is, brief changes in alertness induced by warning signals (Posner, 2008). Visual warning cues (i.e., a double asterisk in the ANT) have shown to increase early perceptual and attentional ERPs as P1 and N1 (Gonçalves et al., 2018; Neuhaus et al., 2010). In tasks wherein auditory signals were used to modulate phasic alertness (i.e., the tone in the ANTI), warning signals also elicited a contingent negative variation (CNV) in central-frontal regions preceding the target (Abundis-Gutiérrez et al., 2014).

Vigilance, defined as the capacity to sustain attention over long periods (Hancock, 2017; Posner, 2008), has been indirectly measured in studies with the ANT or the ANTI task as the behavioral (Fan et al., 2002; Ishigami & Klein, 2010) and neural (Galvao-Carmona et al., 2014; Zani & Proverbio, 2017) responses in the absence of warning and visual signals. As no direct and independent measure of vigilance has been obtained with such attentional networks tasks, differentiating ERPs associated with vigilance within attentional networks has been challenging. Moreover, it has been proposed that vigilance should not be considered as a single mechanism (Esterman & Rothlein, 2019; Oken et al., 2006; Sarter et al., 2001; Shallice et al., 2008; Sturm & Willmes, 2001; van Schie et al., 2021). In this vein, Luna et al. (2018) recently proposed that vigilance can be differentiated between executive and arousal vigilance. Executive vigilance is the ability to monitor and detect critical signals that occur quite rarely during long periods by executing a specific response. The executive vigilance decrement is usually observed as a decrease in correct detection (i.e., hit rate) of critical signals (Warm et al., 2008). Arousal vigilance is the capacity to maintain a fast reaction to environmental stimuli without much control on the response. The arousal vigilance decrement is usually observed as an increase in mean RT, variability of RT, and lapses (i.e., very slow responses) (Lim & Dinges, 2008).

Executive and arousal vigilance are usually measured via different behavioral tasks (Luna et al., 2018; Posner, 2008; Roca et al., 2011). While executive vigilance is measured in signal-detection tasks such as the Sustained Attention to Response Task (Robertson et al., 1997), arousal vigilance is measured in single RT tasks such as the Psychomotor Vigilance Test (Lim & Dinges, 2008). Previous studies in our lab measuring executive and arousal vigilance with embedded tasks in a single session have shown dissociable effects at the neural and physiological levels. While anodal transcranial direct current stimulation over the right fronto-parietal network mitigated the executive but not the arousal vigilance decrement (Hemmerich et al., 2023; Luna et al., 2020), moderate exercise improved executive vigilance and caffeine intake mitigated the arousal vigilance decrement (Sanchis et al., 2020).

ERP studies measuring executive vigilance via signal-detection tasks have found differences in early and late ERPs associated with hits on infrequent signals and correct rejections in the absence of infrequent signals (Karamacoska et al., 2019; McMackin et al., 2020; Reteig et al., 2019). Nonetheless, evidence is both scarce and inconsistent regarding whether the decrease in hits is accompanied by a change in ERPs across time-on-task. Although Boksem et al. (2005) observed a general change in N1 and N2 amplitudes across time-on-task, these changes were not specifically associated with hits. Lara et al. (2018) observed an increase in N1 and a decrease in N2 amplitude as task progressed. However, in Lara et al. no decrement in hits across time-on-task was observed, so changes in ERPs were not accompanied by a decrease in behavioral responses. Interestingly, Bonnefond et al. (2010) observed an increase in a late P1 (at 550–850 ms) with time-on-task in trials that anticipated an infrequent critical signal, an outcome interpreted as an increase in attentional resources for sustaining an optimal performance during long periods.

Arousal vigilance measured with single RT tasks has also been associated with changes in early and late ERPs (Hoedlmoser et al., 2011; Ramautar et al., 2013; Witkowski et al., 2015). Note that, in previous studies measuring arousal vigilance, changes in ERPs were observed across several sessions during a night (Hoedlmoser et al., 2011; Ramautar et al., 2013) or even weeks (Witkowski et al., 2015). In studies wherein arousal vigilance was assessed over one night of sleep deprivation, while Hoedlmoser et al. (2011) observed a decrease in P1 but not N1 at occipital regions, Ramautar et al. (2013) observed reduced P3 peak-latency at central-parietal locations for sleep-deprived participants in contrast to normal-sleep ones. Interestingly, Witkowski et al. (2015) showed that arousal vigilance loss observed during a college semester was accompanied by a decrease in P3 at parieto-occipital regions.

1.1 | The present study

The present study was motivated by some conceptual and methodological limitations observed in previous research on attentional networks, in particular: (a) previous studies analyzing ERPs associated with attentional networks have not directly measured vigilance (Abundis-Gutiérrez et al., 2014; Galvao-Carmona et al., 2014; Gonçalves et al., 2018; Neuhaus et al., 2010; Zani & Proverbio, 2017), and (b) vigilance can be differentiated in executive and arousal vigilance, which are measured via different behavioral tasks (Lim & Dinges, 2008; Luna et al., 2018; Robertson et al., 1997). Noting the above-mentioned limitations, the aim of the present study was to differentiate ERPs associated with attentional networks by simultaneously measuring executive and arousal vigilance along with phasic alertness, orienting, and executive control, within a single session.

To this end, we used the newest and fine-grained version of the ANT, that is, the Attentional Networks Test for Interactions and Vigilance—executive and arousal components (ANTI-Vea, Luna et al., 2018; for a review on the ANT and its variations, see de Souza Almeida et al., 2021). The ANTI-Vea combines three behavioral tasks: (a) the ANTI of Callejas et al. (2004) to assess the independence and interactions of phasic alertness, orienting, and executive control, (b) a signal-detection task to assess executive vigilance, and (c) a single RT task to assess arousal vigilance. Previous studies with the ANTI-Vea have observed the typical main effects and interactions of phasic alertness, orienting, and executive control, along with the executive and arousal vigilance decrements across time-on-task within a single session (Feltmate et al., 2020; Luna et al., 2018; Luna, Barttfeld, et al., 2021; Román-Caballero et al., 2021), both in the laboratory and outside the laboratory in an online session (Luna, Roca, et al., 2021). Importantly, to increase the electroencephalographic (EEG) signal/noise ratio, we decided to run and collapse two experimental sessions per participant.

The predictions for the present study are summarized in Table 1. In particular, we expected similar ERPs for the independence and interactions of phasic alertness, orienting, and executive control as in Abundis-Gutiérrez et al. (2014), as they used the same ANTI task that was embedded in the ANTI-Vea task used in the present study. We also expected executive and arousal vigilance to be associated with changes in different ERPs. Note that previous evidence about changes in ERPs associated with executive (Bonnefond et al., 2010; Lara et al., 2018) and arousal vigilance (Hoedlmoser et al., 2011; Ramautar et al., 2013; Witkowski et al., 2015) seems to be relatively inconsistent. It is important to note that measuring executive and arousal vigilance with different tasks and in different moments is necessarily affected by unrelated changes in the vigilance state, which makes comparing ERPs' changes difficult. Consequently, a crucial aspect of our study is that we measured executive and arousal vigilance along with phasic alertness, orienting, and executive control within a single session. Taking all this into account, we expect the present study to demonstrate that different changes in ERPs associated with attentional networks can be simultaneously observed when attentional networks are measured independently, within a single session, and in the same participant' attentional state (Posner, 2012; Posner et al., 2006).

2 | METHOD

2.1 | Participants

Sample size was a priori estimated based on previous studies with the ANTI-Vea in which the decrement in hits across blocks showed an effect size of $\eta_p^2 = 0.05$ with 40 participants per group (Luna et al., 2018; Luna, Barttfeld, et al., 2021). Using G*Power 3.1.9.4 (Faul et al., 2007), power analysis showed that considering $\alpha = .05$ and $1-\beta = .90$, the minimum sample size required to observe an effect size of $\eta_p^2 = 0.05$ with two sessions and seven blocks was 35 participants. Given that participants performed more than twice the trials than in previous studies with the ANTI-Vea (two sessions of seven blocks, instead of a single session of six blocks), the power of the present study was much higher (Baker et al., 2021).

A total of 40 (34 women) healthy adults (age: M = 25.96; SD = 4.96), who were undergraduate or graduate students from the Universidad Nacional de Córdoba, Argentina, volunteered to participate in the present study. They had normal or corrected to normal vision and none of them had a history of neurological or psychiatric illness. All participants signed an informed consent approved by the local ethics committee. The study was conducted according to the ethical standards of the 1964 Declaration of Helsinki (last update: Seoul, 2008) and was positively evaluated by a local ethics committee (Comité Institucional de Ética de Investigaciones en Salud of the Hospital Nacional de Clínicas, CIEIS HNC, Universidad Nacional de Córdoba, Argentina).

2.2 | Behavioral task: ANTI-Vea

The experimental task was designed and run with E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA, 2012). The ANTI-Vea comprises three embedded subtasks: (a) ANTI (60%), a flanker task combined with an auditory warning signal and a visual spatial cueing paradigm suitable to assess the independence and interactions of phasic alertness, orienting, and executive control; (b) executive vigilance (20%), a signal-detection subtask similar to the Sustained Attention to Response Task wherein an infrequent critical signal has to be detected, thus measuring the executive vigilance decrement; and (c) arousal vigilance (20%), a RT subtask similar to the Psychomotor Vigilance Test suitable to assess the arousal vigilance decrement. The stimuli sequence and timing for the trials of each subtask are depicted in Figure 1 and can be reviewed in detail in

TABLE 1 Summary of event-related potentials expected in the present study based on previous research.

Independent measure	ERPs expected	Previous evidence
Phasic alertness	N1, P2, and CNV	Abundis-Gutiérrez et al. (2014)
Orienting	P1, N1, and P3	Abundis-Gutiérrez et al. (2014)
Executive control	N2 and SP	Abundis-Gutiérrez et al. (2014)
Executive vigilance	P1 and N1	Boksem et al. (2005), Groot et al. (2021), Lara et al. (2018), McMackin et al. (2020), Reteig et al. (2019)
	P3 and late positivity	Bonnefond et al. (2010), Lara et al. (2018)
Arousal Vigilance	Early ERPs (P1 and N1)	Hoedlmoser et al. (2011)

Abbreviations: CNV, contingent negative variation; ERP, event-related potential; SP, slow positivity.

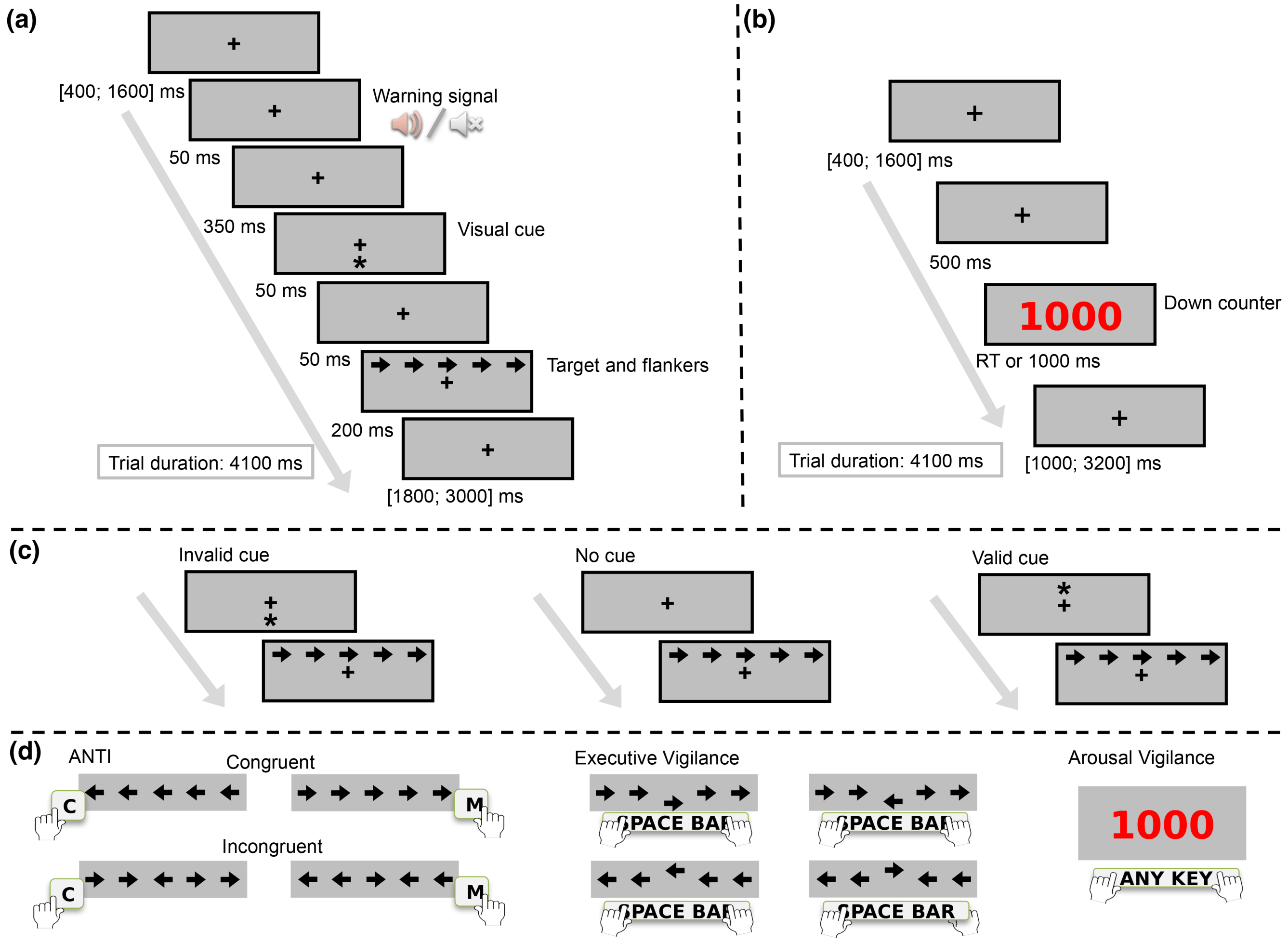

FIGURE 1 Procedure for the three types of trials of the ANTI-Vea task. Stimuli sequence and timing for (a) ANTI and executive vigilance and (b) arousal vigilance trials. In (a), the left panel of target and flankers represents an ANTI trial (centered target), whereas the right one represents an executive vigilance trial (displaced target). (c) Examples of visual cue conditions for measuring the orienting network. (d) Correct responses expected for the ANTI (left), executive vigilance (middle) and arousal vigilance (right) trials. All trials lasted 4100 ms; the initial and final screens had a random timing aiming at making the response' stimuli appearance time unpredictable. In all trials, responses were allowed until 2000 ms.

previous studies (Luna et al., 2018; Luna, Barttfeld, et al., 2021; Luna, Roca, et al., 2021).

Participants were encouraged to fix on the fixation cross at all times. The ANTI trials followed the procedure of the ANTI task (Callejas et al., 2004). In these trials, a five-arrow horizontal string appeared either above or below the fixation point and participants had to select the direction (i.e., left/right) the central arrow (i.e., the target) pointed to, ignoring the direction pointed by the surrounding flanking arrows (see Figure 1 panel d). To assess the executive control network, the direction of the target and flanking arrows were congruent in half of these trials and incongruent in the other half. To assess phasic alertness, a tone (i.e., warning signal) preceded the target in half of these trials, whereas no tone was presented in the other half (see Figure 1 panel a). To assess the orienting network, the target's position (i.e., above/below the fixation point) could be preceded either by a valid (i.e., the same location in 1/3 of ANTI trials), an invalid (i.e., the opposite location in 1/3 of ANTI trials) spatial visual cue, or by no cue at all in the remaining 1/3 of ANTI trials (see Figure 1 panel c). Thus, in ANTI trials wherein the visual cue was present, there were 50% of trials with valid and 50% of trials with invalid spatial visual cue. Importantly, note that valid and invalid conditions were counterbalanced regarding the position of the visual cue on the screen (i.e., above/below the fixation point).

Executive vigilance trials were similar to the ANTI (see Figure 1 panel a), except that the target was largely displaced (i.e., 8 pixels –px–) from its central position, either upward or downward (see Figure 1 panel d). Executive vigilance trials mimic signal-detection tasks like the Sustained Attention to Response Task. Participants were instructed to remain vigilant and detect the infrequent target's displacement by pressing the space bar, ignoring the direction the target pointed to. Lastly, arousal vigilance trials mimic the Psychomotor Vigilance Test. These trials had the same timing as the ANTI and executive vigilance trials but, importantly, no warning signal nor visual cue was presented (i.e., the fixation point remained on the screen) and the target of the ANTI/executive vigilance trials was replaced by a millisecond counter (see Figure 1 panel b). In the arousal vigilance trials, participants had to stop the millisecond counter as fast as possible by pressing any key (see Figure 1 panel d).

2.3 | EEG data acquisition and preprocessing

EEG signal was recorded with a high-density 128-channel BioSemi ActiveTwo system, which was controlled with the ActiView software (BioSemi, Amsterdam). Two flat-type active electrodes were placed over the right and left mastoids as additional electrical reference channels. Electrode's impedance was kept below 1 Ohm. Signal was registered with a sampling rate of 1024 Hz.

EEG data preprocessing was conducted with EEGLAB v2020.0 toolbox (Delorme & Makeig, 2004) on MATLAB R2016a (The MathWorks, Inc.). Data format was first converted to the EEGLAB format and resampled at 512 Hz. The signal was filtered between 0.5 and 45 Hz and then decomposed into 128 components (i.e., the same number of channels) using Independent Component Analysis. Then, using ADJUST v.1.1.1 (Mognon et al., 2011), artifactual components were automatically classified as horizontal eye movements (M = 3.28; SD = 2.51), vertical eye movements (M = 6.85; SD = 5.35), blinks (M = 3.99; SD = 3.24), and generic discontinuities (M = 14.85; SD = 8.56), and were removed from signal. We extracted 3400 ms epochs that were visually inspected to interpolate artifactual channels or to reject the entire epoch if it was too noisy (trials rejected by participant in the collapsed two sessions: M = 10.88; SD = 18.13). Note that the electrodes' montage used here does not include channels above and/or below the eyes and therefore we could not separately register electrooculogram signal. Therefore, although artifactual signal classified by ADJUST as vertical eye movements was removed from EEG signal, specific trials with vertical eye movements after visual cue could not be detected in the present study.

2.4 | Procedure and design

Participants were first familiarized with the task by performing the online ANTI-Vea version (https://www.ugr.es/~neurocog/ANTI/; Luna, Roca, et al., 2021) at any place of their own choosing. To increase the number of within-participant measures of EEG signal, two experimental sessions were completed at the laboratory (average time between sessions: M = 11.80 days; SD = 15.89). The executive and arousal vigilance decrements as well as the main effects and interactions of phasic alertness, orienting, and executive control were observed with the ANTI-Vea in previous research with repeated measures across several sessions (Sanchis et al., 2020). At the laboratory, participants received the standard instructions to perform each type of trial and completed one practice block of 40 (24 ANTI, 8 executive vigilance and 8 arousal vigilance) randomly presented trials, without visual feedback. Each experimental session comprised seven experimental blocks without pause and visual feedback, consisting in 80 (48 ANTI, 16 executive vigilance and 16 arousal vigilance) randomly presented trials within each block. The ANTI trials had the following design: Warning signal (no tone/tone) × Visual cue (invalid/no cue/valid) × Congruency (congruent/incongruent). The 16 executive vigilance trials per block were randomly selected from any possible combination of the ANTI trial design.

2.5 | Statistical analyses

Data analyses were conducted using RStudio 2021.09.1 Build 372 (RStudio Team, 2021) in R (R Core Team, 2021). Behavioral data figures were done with Matplotlib (Hunter, 2007). EEG data figures were done using ggplot2 (Wickham, 2016), purrr (Henry & Wickham, 2020), Rmisc (Hope, 2013), and magrittr (Bache & Wickham, 2020) packages in RStudio for ERPs' plots and MNE-Python code (Gramfort et al., 2013) for topoplots.

Analysis of variance (ANOVA) was conducted with the afex package (Singmann et al., 2021) and planned contrasts were performed with the emmeans package (Lenth, 2021). Effect sizes and the 95% confidence intervals around them for planned contrasts were computed with the effectsize package (Ben-Shachar et al., 2020).

2.5.1 | Behavioral data

Data were analyzed following standard analyses of the ANTI-Vea task (Luna, Barttfeld, et al., 2021), as detailed below. Given that three participants did not complete the second session and one participant was excluded due to an extreme percentage of errors in the ANTI trials (3 SD above the group mean), the final sample included 36 participants (which is indeed a larger sample size than the minimum sample size estimated by power analyses, as detailed in Section 2.1).

Main effects and interactions of phasic alertness, orienting, and executive control, were analyzed in the ANTI trials. In these trials, those with incorrect responses (3.48%) or with RT below 200 ms or above 1500 ms (1.35%) were excluded from RT analysis. Two repeated-measures ANOVAs were separately conducted, with RT or 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-participant factors.

For executive vigilance trials, data were collapsed across warning signal, visual cue, and congruency conditions. Overall executive vigilance performance was described as hits (i.e., correct responses) and misses (i.e., incorrect responses) in executive vigilance trials. For arousal vigilance, following the standard scores computed for the Psychomotor Vigilance Test (Basner & Dinges, 2011), overall arousal vigilance performance was described as fastest and slowest responses in arousal vigilance trials as the first and the fifth quintile of RT, respectively. To avoid the inclusion of trials with RT equal to 0 ms (i.e., 'no responses') in the first quintile, 'no responses' in AV trials (0.36% of AV trials) were excluded from arousal vigilance data analyses. Then, to analyze the executive and arousal vigilance decrements across time-on-task, data were computed as a function of blocks of trials. Executive vigilance decrement was analyzed with a repeated-measures ANOVA, with hits as dependent variable and including blocks (seven levels) as a within-participant factor. Arousal vigilance decrement was analyzed with a repeated-measures ANOVA, with mean RT in arousal vigilance trials as dependent variable and blocks (seven levels) as a within-participant factor.

Partial eta-squared (η_p^2) and 95% confidence intervals around them (Cumming, 2014) are reported as measure of the ANOVAs' effect size (Kelley & Preacher, 2012). If the sphericity assumption was violated (i.e., Mauchly's test $p<.05$), degrees of freedom are reported with Greenhouse–Geisser correction. Polynomial contrasts were conducted to analyze the significance of the linear executive/arousal vigilance decrement across blocks.

2.5.2 | EEG data

Analyses were separately conducted as a function of the independent measures of the ANTI-Vea. ERPs of interest were examined based on previous research on attentional networks, as detailed below. All analyses were performed on baseline corrected epochs, using the 200-ms signal preceding the locking stimuli as the baseline. Early ERPs (P1, N1, P2, and N2) were analyzed measuring peak amplitude and late ERPs (CNV, P3, and SP) measuring adaptive mean amplitude as dependent variable, respectively. In all ERPs analyses, Cohens' *d* (for *t* tests) or partial eta-squared (η_p^2; for ANOVAs) are reported as effect size score, with 95% confidence intervals around them (Cumming, 2014; Kelley & Preacher, 2012).

ERPs associated with the independence and interactions of phasic alertness, orienting, and executive control, were analyzed following the analyses reported by Abundis-Gutiérrez et al. (2014). Note that ERPs were examined in the same set of trials in which mean correct RT performance was analyzed (see above Section 2.5.1). Epochs were warning signal-locked (from 200 ms before to 800 ms after) or target-locked (from 200 ms before to 1000 ms after).

Independent effects of phasic alertness, orienting, and executive control, were analyzed by paired *t* tests, as follows. For phasic alertness, no tone versus tone conditions were contrasted for warning signal-locked N1 (230–300 ms), P2 (300–400 ms), and CNV (400–600 ms) at Fcz. For the orienting network, invalid versus valid conditions were contrasted for target-locked P1 and N1 (100–230 ms) at the average of Oz, O1, and O2 channels, and P3 (350–650 ms) was analyzed at the average of Pz and CPz channels. Given the short stimuli onset asynchrony (SOA) (100 ms) between visual cue and target stimuli, we cannot interpret ERPs of interest for the orienting network as changes in EEG signal evoked by the target, especially for P1 and N1. Therefore, target-locked contrasts of interest for the orienting network were plotted and interpreted as a function of the difference wave between validity conditions in the time window of each ERP of interest (Zani & Proverbio, 2017). For the executive control network, given that in our data N2 was not observed in Fcz (i.e., the channel analyzed in Abundis-Gutiérrez et al., 2014) nor in the surrounding channels to Fcz, congruent versus incongruent conditions were contrasted for target-locked N2 (250–400 ms) in the central channels closest to Fcz, that is, at CPz and adjacent channels (i.e., one posterior and one anterior to CPz), and SP (500–800 ms) at Pz. The modulations of phasic alertness (no tone/tone) or orienting (invalid/valid) on executive control (congruent/incongruent) were analyzed by separated repeated-measures ANOVAs, for target-locked N2 (250–400 ms) at CPz and adjacent channels and SP (500–800 ms) at Pz.

Importantly, given the short SOA between the visual cue and the target in the current procedure, there could be a consistent distortion induced by the preceding visual cue stimuli in target-locked ERPs, particularly in the orienting and orienting by congruency contrasts. In order to control such potential distortion by the presence of visual cue stimuli in ERPs of interest for the orienting network, Figures S1 and S2 depict EEG signal in the no cue condition along with invalid/valid conditions of cueing. Note that, critically, Figures S1 and S2 show a similar baseline for no cue and invalid/valid conditions, and in Figure S2, N2 is observed in the same time window in the no cue and the valid/invalid conditions.

ERPs associated with vigilance were analyzed following two approaches: (a) as a function of overall performance and (b) as a function of performance across time-on-task. To increase the number of trials in analyses of ERPs as a function of time-on-task, first and second blocks and the sixth and seventh blocks were collapsed as the initial and last period, respectively. For executive vigilance, ERPs of overall responses were compared as a function of hits or misses in executive vigilance trials and ERPs across time-on-task were analyzed as a function of hits in the initial and last period of the task. Epochs were target-locked (from 200 ms before to 1000 ms after) in executive vigilance trials and ERPs of interest were analyzed by paired *t* tests in channels based on previous research with signal-detection tasks (Bonnefond et al., 2010; Groot et al., 2021; Lara et al., 2018; McMackin et al., 2020; Reteig et al., 2019), in particular: P1 (100–200 ms), N1 (140–230 ms), and P3 (350–650 ms) at Pz and SP (500–800 ms) at Cz and adjacent channels. Given that clear peaks were not observed in P1 and N1 in executive vigilance contrasts, ERPs for executive vigilance contrasts were analyzed as a function of adaptive mean amplitude (Martín-Arévalo et al., 2015).

For arousal vigilance, ERPs of overall responses were compared as a function of the fastest and slowest RT in arousal vigilance trials (Basner & Dinges, 2011) and ERPs across time-on-task were analyzed as a function of responses in arousal vigilance trials of the first and the last period of the task. Epochs were target-locked (from 200 ms before to 1000 ms after) in arousal vigilance trials. ERPs of interest were analyzed by paired *t* tests in channels based on previous research with single RT tasks (Hoedlmoser et al., 2011), in particular: N1 (200–300 ms) and P2 (350–650 ms) in Oz, O1, and O2 channels.

3 | RESULTS

3.1 | Behavioral performance

3.1.1 | Phasic alertness, orienting, and executive control

All typical main effects usually observed with the ANTI (Callejas et al., 2004) and ANTI-Vea (Luna et al., 2018; Luna, Roca, et al., 2021) tasks were observed as significant here (see Figure 2). For warning signal {RT: [F (1, 35) = 109.61, $p < .001$, $\eta_p^2 = 0.76$, 95% CI (0.60, 0.84)]; errors: [F (1, 35) = 15.94, $p < .001$, $\eta_p^2 = 0.31$, (0.08, 0.52)]}, responses were faster and more precise in the tone than in the no tone condition. The visual cue main effect {RT: [F (1.98, 69.27) = 79.22, $p < .001$, $\eta_p^2 = 0.69$, (0.57, 0.77)]; errors: [F (1.90, 66.43) = 3.39, p = .042, $\eta_p^2 = 0.09$, (0.00, 0.23)]} showed the typical validity {invalid > valid: only for RT [t (35) = 12.12, $p < .001$, d = 2.05, 95% CI (1.46, 2.63)]; not for errors: [t (35) = −1.67, p = .232, d = −0.28, (−0.62, 0.06)]}, benefits {no cue > valid: RT [t (35) = 7.62, $p < .001$, d = 1.29, (0.84, 1.73)]; although reversed for errors: [t (35) = −2.60, p = .035, d = −0.44, (−0.78, −0.09)]} and costs {invalid > no cue: only for RT [t (35) = 4.91, $p < .001$, d = 0.83, (0.44, 1.21)]; not for errors: [t (35) = 0.73, p = .748, d = 0.12, (−0.21, 0.45)]} effects. For congruency {only for RT: [F (1, 35) = 106.85, $p < .001$, $\eta_p^2 = 0.75$, (0.60, 0.84)]; not for errors: [F (1, 35) = 0.03, p = .853, $\eta_p^2 < 0.01$, (0.00, 0.09)]}, responses were faster in the congruent than incongruent condition.

The two-way interactions usually observed with the ANTI (Callejas et al., 2004) and the ANTI-Vea (Luna et al., 2018; Luna, Roca, et al., 2021) were observed as significant only for RT as dependent variable (see Table 2): Warning signal × Visual cue {RT: [F (1.87, 65.43) = 60.27, $p < .001$, $\eta_p^2 = 0.63$, (0.49, 0.73)]; errors: [F (1.73, 60.48) = 0.78, p = .445, $\eta_p^2 = 0.02$, (0.00, 0.11)]}, Warning signal × Congruency {RT: [F (1, 35) = 20.64, $p < .001$, $\eta_p^2 = 0.37$, (0.13, 0.57)]; errors: [F (1, 35) = 0.90, p = .350, $\eta_p^2 = 0.03$, (0.00, 0.20)]}, and Visual cue × Congruency {RT: [F (1.90, 66.34) = 5.33, p = .008, $\eta_p^2 = 0.13$, (0.01, 0.28)]; errors: [F (1.97, 68.86) = 0.26, p = .765, $\eta_p^2 < 0.01$, (0.00, 0.07)]}.

3.1.2 | Executive and arousal vigilance

As usually observed with the ANTI-Vea (Luna et al., 2018; Luna, Roca, et al., 2021), the executive vigilance decrement was observed as a significant decrease in hits across blocks [F(4.64, 162.43) = 9.05, $p < .001$, $\eta_p^2 = 0.21$, (0.10, 0.28)] with a significant linear component [t (35) = −5.14, $p < .001$, $\eta_p^2 = 0.43$, (0.22, 1.00)] (see Figure 3). Unexpectedly, however, the arousal vigilance decrement was not observed: the main effect of mean RT across blocks was not significant [F (3.93, 137.49) = 0.45, p = .769, $\eta_p^2 = 0.01$, (0.00, 0.02)] (see also Figure 3).

Overall performance of executive and arousal vigilance is reported in Table 3.

3.2 | Event-related potentials

3.2.1 | Phasic alertness, orienting, and executive control

ERPs similar to those observed by Abundis-Gutiérrez et al. (2014) were found here. For phasic

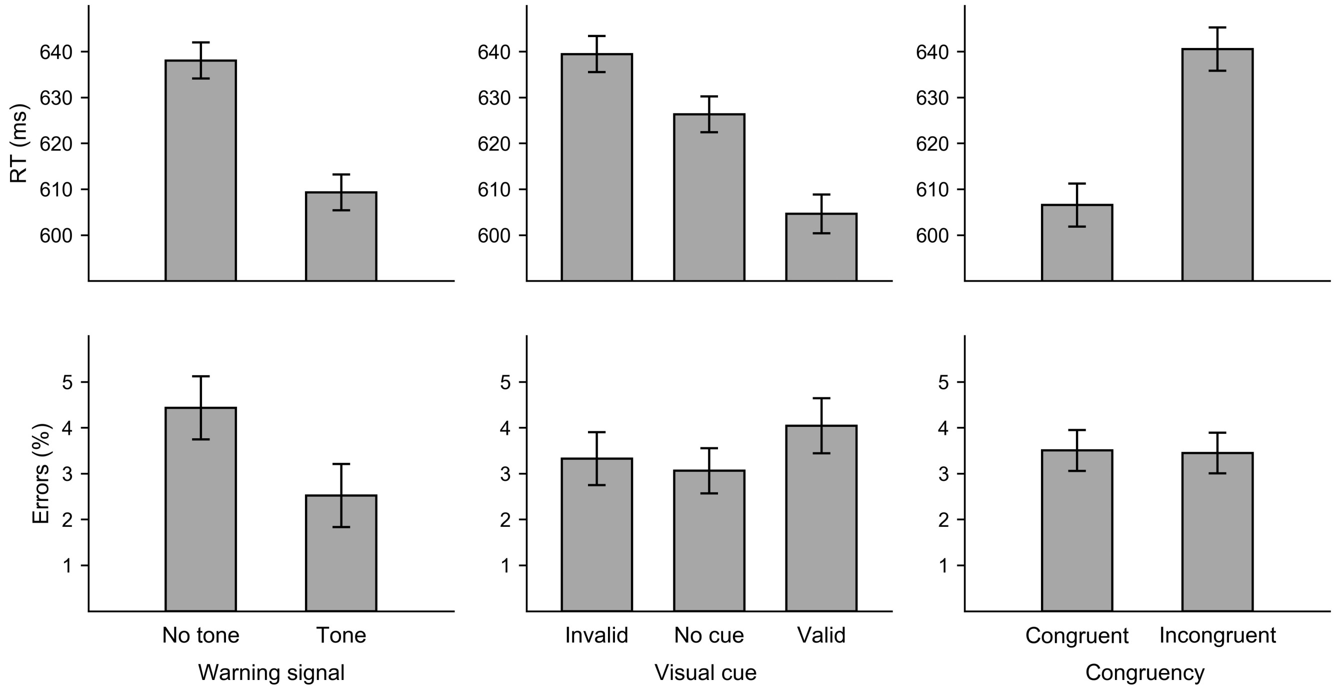

FIGURE 2 Mean correct RT (superior graphs) and percentage of errors (bottom graphs) for warning signal (left panels), visual cue (center panels), and congruency (right panels) conditions. Error bars represent 95% CI of the mean and were computed following the Cousineau–Morey method (Morey, 2008).

TABLE 2 Mean correct RT and percentage of errors as a function warning signal, visual cue, and congruency conditions.

	Reaction time (ms)				Errors (%)			
	Congruent		Incongruent		Congruent		Incongruent	
	M	95% CI	M	95% CI	M	95% CI	M	95% CI
No tone								
Invalid	630	[595, 665]	663	[630, 695]	4.02	[2.55, 5.49]	4.17	[2.77, 5.54]
No cue	641	[608, 674]	659	[629, 690]	4.27	[2.60, 5.93]	4.07	[2.74, 5.40]
Valid	604	[572, 636]	630	[598, 663]	5.46	[3.82, 7.09]	4.61	[2.65, 6.57]
Tone								
Invalid	608	[577, 639]	657	[624, 691]	2.48	[1.62, 3.34]	2.63	[1.53, 3.72]
No cue	582	[553, 611]	624	[595, 653]	1.88	[0.97, 2.80]	2.03	[1.16, 2.90]
Valid	575	[545, 605]	610	[579, 641]	2.93	[1.67, 4.18]	3.17	[2.17, 4.18]

Abbreviations: CI, confidence intervals; M, mean.

alertness, significant and relatively large differences were found between tone and no tone conditions in N1 [t (35) = −8.14, $p < .001$, d = −1.36, (−1.83, −0.91)], P2 [t (35) = 9.07, $p < .001$, d = 1.51, (1.04, 2.02)], and CNV [t (35) = −4.91, $p < .001$, d = −0.82, (−1.21, −0.44)] for warning-signal locked ERPs at FCz (see Figure 4).

For the orienting network, there were no significant differences between cueing validity conditions in the time windows of P1 [t (35) = 0.07, p = .941, d = −0.01, (−0.34, 0.32)] and N1 [t (35) = −1.17, p = .251, d = −0.19, (−0.53, 0.14)] at occipital channels, as depicted by the flat difference wave in Figure 4. Similarly, no significant differences

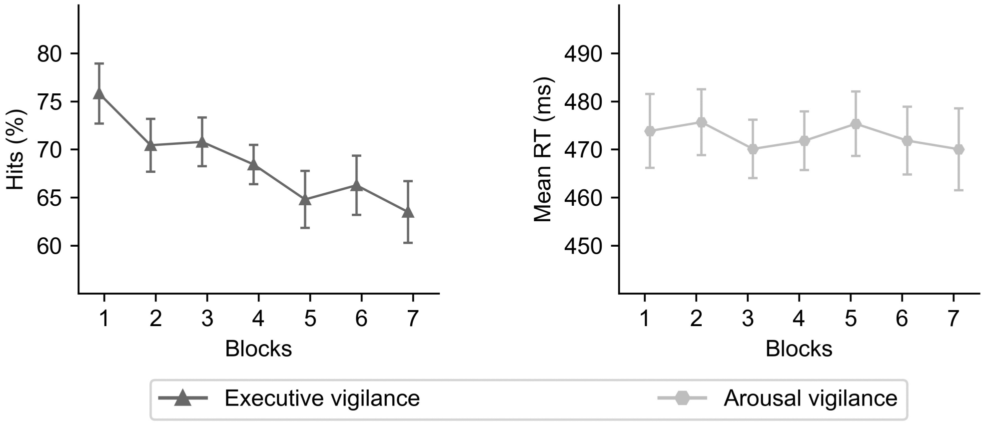

FIGURE 3 Executive (left panel) and arousal (right panel) vigilance performance across blocks. Error bars represent 95% CI of the mean and were computed following the Cousineau–Morey method (Morey, 2008).

TABLE 3 Descriptive statistics for responses in executive and arousal vigilance subtasks.

	N	Min	Max	M	95% CI
Executive vigilance					
Hits	164.81	68	212	73.57%	[67.57, 79.58]
Misses	59.19	12	156	26.43%	[20.42, 32.43]
Arousal vigilance					
Fastest	44.89	42	45	386 ms	[362, 409]
Slowest	43.92	41	44	594 ms	[555, 632]

Note: *N* represents the mean number of trials in which that response was observed, with its respective Min and Max across participants. M represents the mean performance in that score, with its respective variability (i.e., 95% CI around the mean).

Abbreviations: CI, confidence intervals; M, mean; Max, maximum, Min, minimum, *N*, absolute frequency per participant, .

were observed in the time window of P3 at CPz and Pz, [t (35) = 1.30, p = .201, d = 0.22, (−0.12, 0.55)], as shown by the flat difference wave between validity conditions in the same Figure 4.

Lastly, for the executive control network, significant differences were observed between congruency conditions in N2 at CPz and adjacent channels [t (35) = 2.20, p = .034, d = 0.37, (0.03, 0.71)] and SP at Pz [t (35) = 3.27, p = .002, d = 0.54, (0.19, 0.90)] target-locked contrasts (see Figure 5).

Regarding the modulations analyzed in Abundis-Gutiérrez et al. (2014), SP at Pz for executive control was not modulated by phasic alertness [F (1, 35) = 0.26, p = .612, $\eta_p^2 < 0.01$, (0.00, 0.15)] nor orienting [F (1, 35) = 0.75, p = .391, η_p^2 = 0.02, (0.00, 0.19)] conditions. However, N2 at CPz and adjacent channels for executive control was significantly modulated although only by orienting [F (1, 35) = 5.80, p = .021, η_p^2 = 0.14, (0.00, 0.36)] (see Figure 5), not by phasic alertness [F (1, 35) = 0.27, p = .604, $\eta_p^2 < 0.01$, (0.00, 0.15)]. Opposite differences between congruent and incongruent conditions were observed for valid and invalid conditions, although pairwise comparisons showed that no N2 difference was significant: valid cue [t (35) = −1.94, p = .061, d = −0.33, (−0.67, 0.01)] and invalid cue [t (35) = 1.67, p = .104, d = 0.28, (−0.06, 0.62)].

3.2.2 | Executive vigilance

As can be observed in Figure 6, contrasts between overall hits and misses showed a significant (although with a relatively small effect size) larger amplitude in P1 in hits than misses, [t (35) = 2.28, p = .029, d = 0.38, (0.04, 0.73)], but no significant differences in N1 [t (35) = 0.58, p = .560, d = 0.10, (−0.23, 0.43)] and P3 [t (35) = −0.62, p = .538, d = −0.10, (−0.44, 0.23)] in Pz. The SP did not show a significant difference between hits and misses in Cz and adjacent channels, [t (35) = 2.01, p = .052, d = 0.34, (0.00, 0.68)].

Importantly, as depicted in Figure 6, the decrement in hits was accompanied by a significant change in ERP amplitude across time-on-task. Regarding early ERPs in Pz, analysis on predefined time windows showed no significant

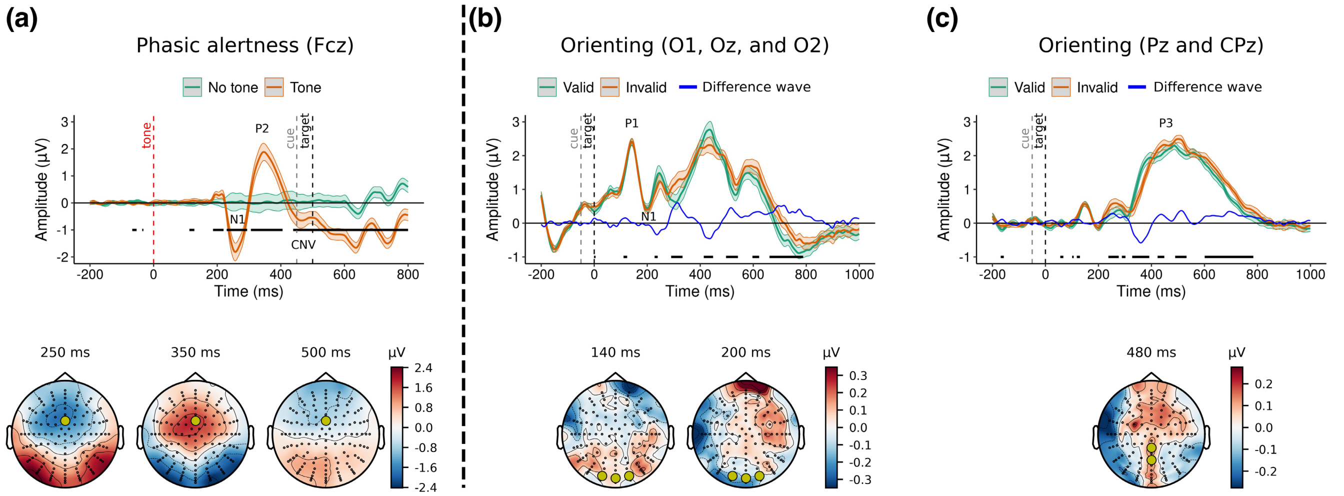

FIGURE 4 Event-related potentials associated with (a) phasic alertness and (b) the orienting network. (a) Signal amplitude as a function of warning signal condition (no tone/tone) at Fcz, locked at warning signal stimuli (dashed vertical red line). Signal amplitude locked at target stimuli (dashed vertical black line) as a function of cueing validity (valid/invalid, presented at the dashed vertical gray line) at the average of (b) O1, Oz, and O2 channels for P1 and N1 components and (c) CPz and Pz channels for P3 component. In (b) and (c), the difference wave represents mean difference between invalid and valid signal. Significant differences ($p < .05$) between conditions at each time point are highlighted with a black line above the x-axis. Shadowed traces around mean signal represent within-participant 95% CI of mean for that condition and were computed with the Cousineau–Morey method (Morey, 2008). Topoplots represent tone minus no tone signal in (a) and invalid minus valid signal in (b) and (c). Channels of interest (named in each figure title) are highlighted with a yellow marker on each topoplot.

change in both P1 [*t* (35) = 1.08, *p* = .286, *d* = 0.18, (−0.15, 0.52)] and N1 [*t* (35) = 1.14, *p* = .258, *d* = 0.19, (−0.14, 0.53)] amplitude across task periods. However, the pattern depicted in Figure 6 shows significant differences across task periods in N1. A posteriori analysis in a reduced time window (180–210 ms) close to N1 peak confirmed relatively small and significant decreases in N1 amplitude across task period [*t* (35) = 2.34, *p* = .025, *d* = 0.39, (0.05, 0.74)]. In addition, significant increases in both P3 at Pz [*t* (35) = 2.14, *p* = .039, *d* = 0.36, (0.02, 0.70)] and SP at Cz and adjacent channels [*t* (35) = 3.44, *p* = .002, *d* = 0.57, (0.22, 0.94)] were observed between the first and the last period of the task.

3.2.3 | Arousal vigilance

Significant differences in ERPs among trials with fastest and slowest arousal vigilance responses were observed in occipital channels of interest (see Figure 7). In particular, N1 showed a smaller amplitude for the slowest than for the fastest responses, but only in O1 [*t* (35) = 2.50, *p* = .017, *d* = 0.42, (0.07, 0.76)]; the difference was clearly not significant in Oz [*t* (35) = 1.68, *p* = .101, *d* = 0.28, (−0.06, 0.62)] and O2 [*t* (35) = 0.64, *p* = .528, *d* = 0.11, (−0.23, 0.44)]. Regarding P2, peak amplitude was significantly smaller for the slowest than for the fastest responses in all occipital channels of interest: O1 [*t* (35) = −3.57, *p* = .001, *d* = −0.59, (−0.96, −0.24)], Oz [*t* (35) = −2.86, *p* = .007, *d* = −0.48, (−0.83, −0.13)], and O2 [*t* (35) = −2.83, *p* = .008, *d* = −0.47, (−0.82, −0.13)].

Lastly, ERPs of interest did not significantly change across task period, in agreement with the lack of behavioral decrement in mean RT. N1 amplitude was not significantly different between the first and last task period in O1 [*t* (35) = 0.92, *p* = .364, *d* = 0.15, (−0.18, 0.49)], Oz [*t* (35) = 1.63, *p* = .113, *d* = 0.27, (−0.06, 0.61)], and O2 [*t* (35) = 1.62, *p* = .115, *d* = 0.27, (−0.07, 0.61)]. Similarly, P2 did not significantly change between the first and last task period in O1 [*t* (35) = −0.37, *p* = .714, *d* = −0.06, (−0.39, 0.27)], Oz [*t* (35) = −0.63, *p* = .524, *d* = −0.11, (−0.44, 0.22)], and O2 [*t* (35) = −0.70, *p* = .488, *d* = −0.12, (−0.45, 0.21)].

4 | Discussion

The present study aimed to differentiate ERPs associated with attentional networks by simultaneously measuring phasic alertness, orienting, and executive control, along with executive and arousal vigilance (Posner, 2012; Posner et al., 2006). Previous studies on ERPs associated with attentional networks have used tasks like the ANT or the ANTI, in which independent measures of phasic alertness, orienting, and executive control were obtained (Abundis-Gutiérrez et al., 2014; Galvao-Carmona

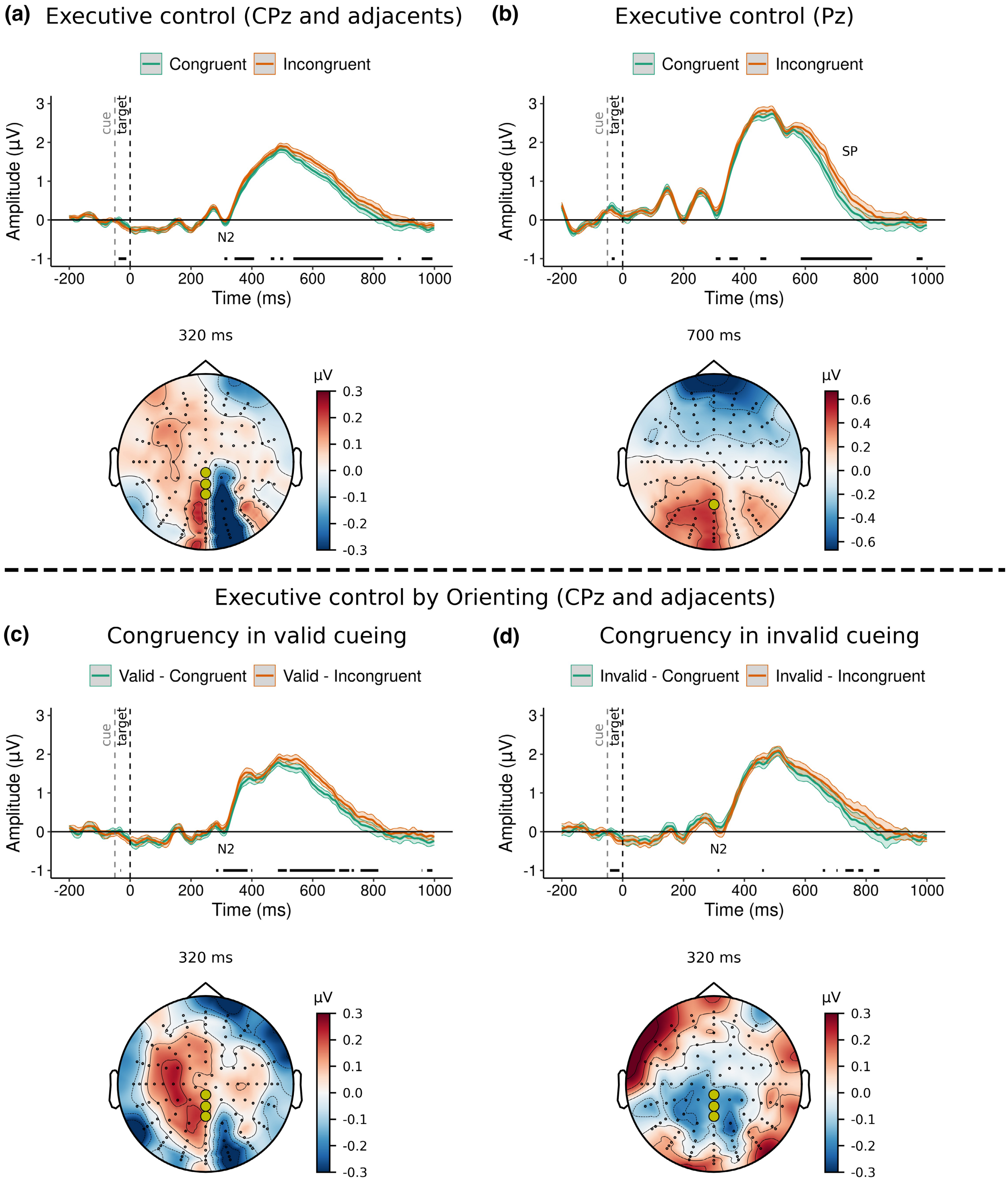

FIGURE 5 Event-related potentials associated with the executive control network (a and b) and with the executive control network modulated by the cueing validity effect (c and d). Signal amplitude target-locked as a function of congruency at (a) the average of CPz and adjacent channels for N2 component and (b) Pz channel for SP component. Signal amplitude target-locked as a function of congruency at the average of CPz and adjacent channels for N2 component in (c) valid cue condition and (d) invalid cue condition. The visual cue (dashed vertical gray line) is presented 50 ms before the target (dashed vertical black line). In all amplitude signal plots, significant differences ($p < .05$) between conditions at each time point are highlighted with a black line above the x-axis. Shadowed traces around mean signal represent within-participant 95% CI of mean for that condition and were computed with the Cousineau–Morey method (Morey, 2008). Topoplots represent incongruent minus congruent signal in (a) and (b), and incongruent minus congruent signal in valid (c) and invalid (d) trials. Channels of interest (named in each figure title) are highlighted with a yellow marker on each topoplot.

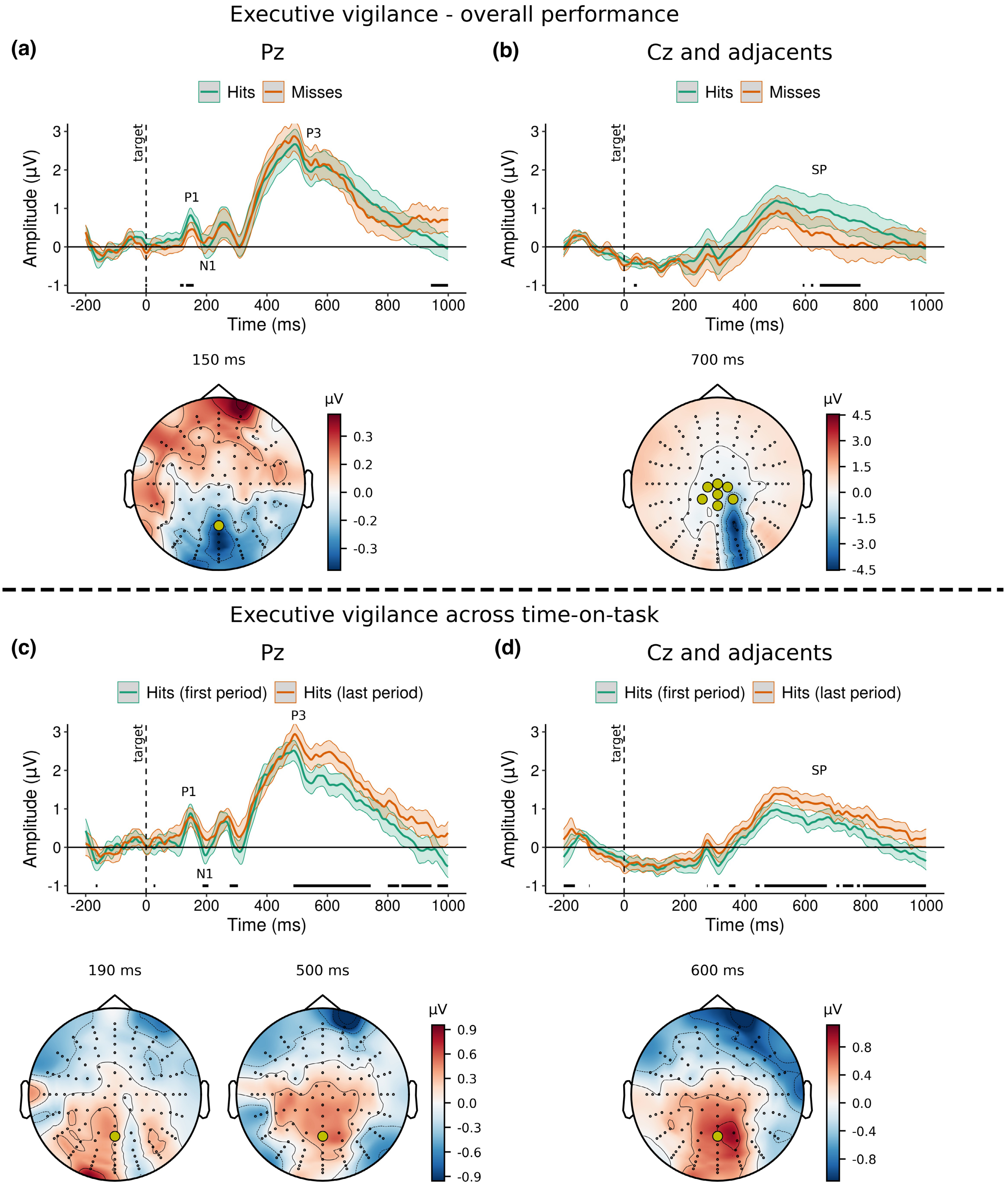

FIGURE 6 Event-related potentials associated with executive vigilance as a function of overall performance (a and b) and the decrease in hits (c and). Signal amplitude target-locked as a function of hits and misses at (a) Pz for P1, N1, and P3 components and (b) Cz and adjacent channels for SP component. Signal amplitude target-locked for hits as a function of task period (first/last) at (c) Pz for P1, N1, and P3 components and (d) Cz and adjacent channels for SP component. In all amplitude signal plots, significant differences ($p < .05$) between conditions at each time point are highlighted with a black line above the x-axis. Shadowed traces around mean signal represent within-participant 95% CI of mean for that condition and were computed with the Cousineau–Morey method (Morey, 2008). Topoplots represent misses minus hits signal in (a) and (b), and last minus first period signal for hits in (c) and (d). Channels of interest (named in each figure title) are highlighted with a yellow marker on each topoplot.

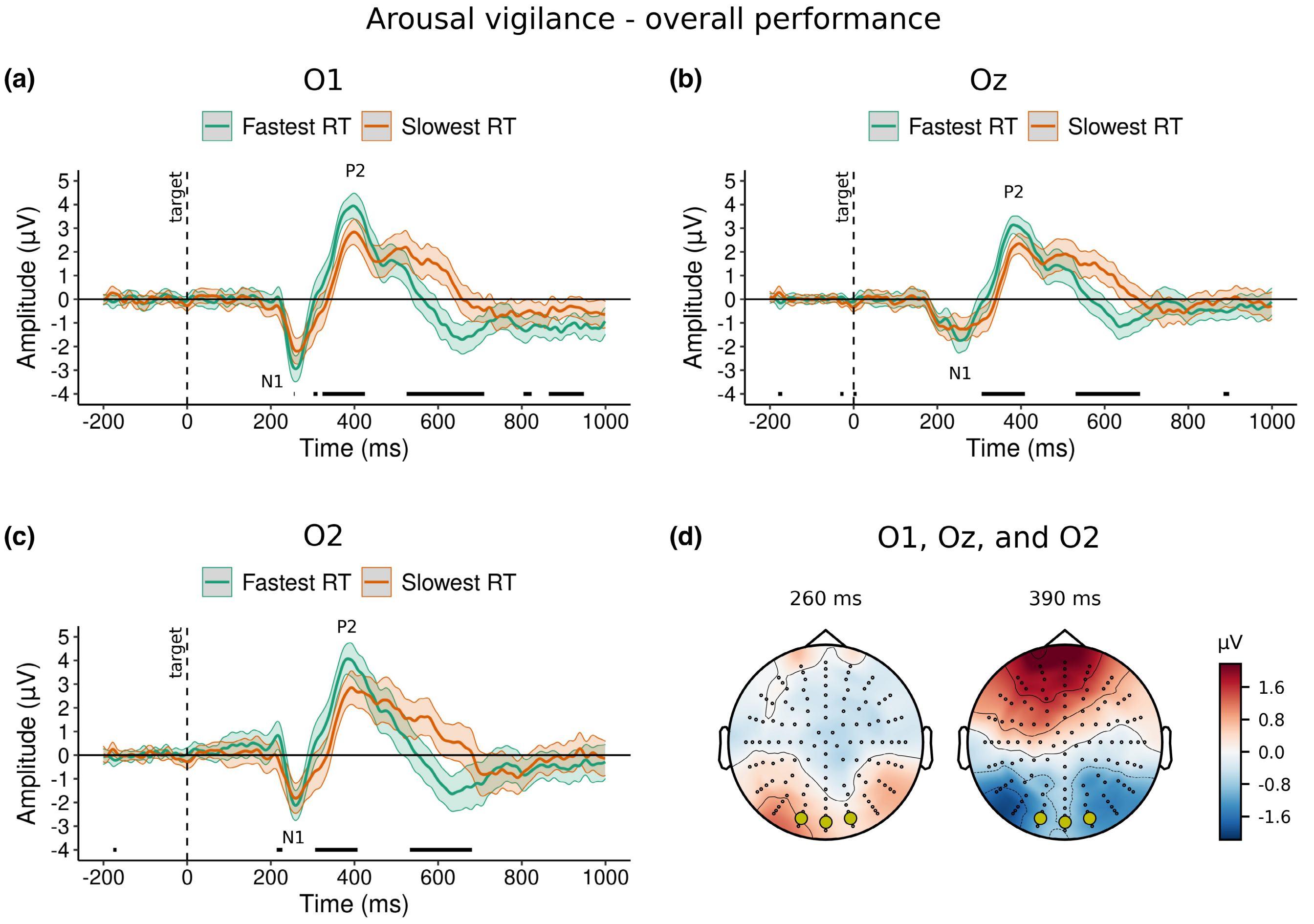

FIGURE 7 Event-related potentials associated with arousal vigilance performance. Signal amplitude target-locked as a function of reaction time (fastest/slowest) at (a) O1, (b) Oz, and (c) O2, for N1 and P2 components. In all amplitude signal plots (a, b, and c), significant differences ($p < .05$) between conditions at each time point are highlighted with a black line above the x-axis. Shadowed traces around mean signal represent within-participant 95% CI of mean for that condition and were computed with the Cousineau–Morey method (Morey, 2008). (d) Topoplots represent slowest minus fastest reaction time' signal for N1 (260 ms) and P2 (390 ms). In all topoplots, channels of interest are represented with a yellow marker for that component.

et al., 2014; Gonçalves et al., 2018; Neuhaus et al., 2010; Zani & Proverbio, 2017). In contrast, ERPs associated with vigilance have been studied using different tasks and in relative isolation, by measuring executive vigilance via signal-detection tasks (Bonnefond et al., 2010; Lara et al., 2018; Reteig et al., 2019) or arousal vigilance via single RT tasks (Hoedlmoser et al., 2011; Ramautar et al., 2013; Witkowski et al., 2015). Therefore, ERPs associated with vigilance have been measured in different contexts and with different task sets, with participants likely in different attentional states. In the present study, ERPs associated with attentional networks were examined with the ANTI-Vea (Luna et al., 2018), a task that simultaneously measures phasic alertness, orienting, and executive control, as well as executive and arousal vigilance.

ERPs previously observed by Abundis-Gutiérrez et al. (2014) for phasic alertness, orienting, and executive control, were replicated here. For phasic alertness, warning signal reduced RT and modulated early ERPs associated with attentional preparation as N1 and P2 (Jonkman, 2006) and a CNV as an anticipatory state prior to target onset in central-frontal regions (Abundis-Gutiérrez et al., 2014). Note that N1 and P2 might be more associated with the salience of the tone than with changes in phasic alertness state. Importantly, Petersen and Posner (2012) proposed the CNV as a critical mechanism of the alerting network, an ERP originated in frontal-central regions such as the anterior cingulate cortex and adjacent structures. The CNV is generally observed between the warning signal and the target and has been associated with a temporal inhibition of the current behavioral activity to prepare the response for a fast reaction to an incoming target (Petersen & Posner, 2012).

Previous research with attentional networks tasks showed that the CNV might be elicited both by visual (Galvao-Carmona et al., 2014) and auditory

(Abundis-Gutiérrez et al., 2014) warning signals. Galvao-Carmona et al. (2014) observed that CNV's amplitude increases as a function of the information provided by the anticipatory signal. Using a modified version of the ANT, Galvao-Carmona et al. observed that CNV was larger when the target was preceded by a 100% predictive visual spatial cue—for measuring orienting—than by a not spatially predictive visual central cue—for measuring phasic alertness. Note that, however, in Galvao-Carmona et al., the SOA between visual cues and the target was larger (1000 ms) than in the present study (500 ms between tone and target), which could increase response's preparation for the incoming target in both visual cue conditions. Moreover, it has been proposed that while auditory signals are more effective than visual cues to modulate phasic alertness (Fernandez-Duque & Posner, 1997; Petersen et al., 2017), cueing validity paradigms are more effective than 100% predictive cues for measuring orienting (Posner, 2016). Thus, as observed in the present study, the CNV is probably more associated with phasic alertness changes evoked by warning signals (either spatially informative or not) that increase temporal preparation for the incoming target (Pauletti et al., 2014) than with orienting mechanisms to anticipate target localization (Galvao-Carmona et al., 2014).

Regarding the orienting network, visual spatial cues did not modulate early ERPs in occipital regions, showing a similar signal between valid and invalid conditions in time windows for P1 and N1. Previous studies with the ANT have shown increased target-locked N1 when spatial cues are 100% predictive about target localization (Gonçalves et al., 2018; Neuhaus et al., 2010). It has been reported that when exogenous cues reorient attention to lateralized targets, cueing validity modulates P1 and N1 (Fu et al., 2001, 2005; Talsma et al., 2007). In the present study, however, exogenous cues preceded target localization at central positions, which might have reduced validity effects for target detection, as documented in Abundis-Gutiérrez et al. (2014). In addition, a similar signal in the time window for P3 in central-parietal regions was observed between invalid and valid cueing conditions (Correa et al., 2006; Randall & Smith, 2011; Talsma et al., 2007). Previous research has found increased P3 after invalid cueing, which has been explained as a cost of disengaging and reorienting attention (Abundis-Gutiérrez et al., 2014) and as the inhibition of the representation of a planned movement to activate a newly demanded response (Randall & Smith, 2011).

For the executive control network, flankers' interference reduced N2 and increased SP amplitudes, as reported in Abundis-Gutiérrez et al. (2014). Some studies conducted with the ANT observed changes in P3 associated with executive control (Galvao-Carmona et al., 2014; Gonçalves et al., 2018; Neuhaus et al., 2010). In contrast, Abundis-Gutiérrez et al. dissociated two ERPs within the executive control network: N2 for conflict detection and SP for postconflict resolution. Previous research has extensively associated N2 with conflict detection and response inhibition (Folstein & Van Petten, 2008; Swainson et al., 2003). While in some visual paradigms N2 has been observed in the posterior scalp, as in the present study, in auditory paradigms N2 has been observed in frontal areas with the anterior cingulate cortex as the source region (Folstein & Van Petten, 2008), that is, a brain region associated with conflict detection (Botvinick et al., 2001, 2004; Yeung et al., 2004). Further research supports N2 as a key ERP associated with executive control: while increased N2 latency and reduced N2 amplitude have been associated with cognitive control loss across aging (Kropotov et al., 2016), transcutaneous vagus nerve stimulation has shown to improve sequential conflict adaptation by reducing N2 amplitude (Fischer et al., 2018).

Regarding SP, also known as error positivity, previous research has observed this ERP around 200–400 ms after response and it has been associated with error resolution, independently of conflict and stimuli modality (West, 2003; West & Moore, 2005). Following Abundis-Gutiérrez et al. (2014), the fact that SP has been observed either before, during, or after the motor response might indicate that SP is associated with post-target processing rather than with motor preparation. The increase in SP amplitude has been associated with error commission awareness in cognitive control tasks (Endrass et al., 2012) and cognitive control decline across aging (Larson et al., 2016). Altogether, the present and previous findings support N2 and SP as two key ERPs associated with the executive control network (Posner, 2012; Posner et al., 2006).

Importantly, contrary to Abundis-Gutiérrez et al. (2014), N2 associated with executive control was modulated by the orienting network. Previous research has shown that N2 is likely to be modulated by temporal orienting of attention, as invalid cues increase N2 amplitude impairing conflict detection (Correa et al., 2006). In our study, the N2 effect (i.e., more negative for incongruent than congruent condition) was only observed for invalid trials, being reversed for valid ones. However, pairwise comparisons showed that no effect reached significance, limiting the interpretation of this outcome. In a study conducted with the ANT, modulations of orienting over SP have been observed (Zani & Proverbio, 2017). Nevertheless, as previously discussed, while in the ANT the spatial cue is 100% predictive about target localization, the cueing validity paradigm embedded in the ANTI and ANTI-Vea also measures benefit and cost effects (Callejas et al., 2004, 2005; Posner, 2016). Although the attentional networks model anticipates interactions among the networks (Petersen & Posner, 2012; Posner & Petersen, 1990), in the present study, N2 modulation by the orienting network was the only interaction observed. Nonetheless, evidence on ERPs with attentional networks tasks measuring interactions among the networks is still scarce (Abundis-Gutiérrez et al., 2014). Further research is, therefore, necessary to examine potential interactions among attentional networks in ERPs.

Regarding vigilance, different ERPs were observed in the same task period for executive and arousal vigilance. To the best of our knowledge, this is the first study in analyzing ERPs associated with attentional networks including independent measures of executive and arousal vigilance in the same task. Previously, Galvao-Carmona et al. (2014) observed a slow CNV prior the target onset in the no cue condition of the ANT, which was interpreted as a general level of tonic alerting or vigilance. However, the no cue condition in the ANT is not a direct measure of vigilance (Ishigami & Klein, 2010; Roca et al., 2011), which limits the analysis of a clear ERP associated with vigilance. In the present study, by simultaneously measuring executive and arousal vigilance via independent subtasks embedded in the ANTI-Vea (Luna et al., 2018), different ERPs were associated with changes in vigilance. In short, while the executive vigilance decrement was associated with increased amplitude in late ERPs (i.e., P3 and SP), arousal vigilance loss was associated with reduced amplitude in early ERPs (i.e., N1 and P2). Importantly, the present outcomes further support different neural changes for executive and arousal vigilance (Luna et al., 2020; Luna et al., 2022) as part of attentional networks (Petersen & Posner, 2012; Posner & Petersen, 1990).

In particular, for executive vigilance, we observed similar ERPs as those reported in previous studies with signal-detection tasks (Boksem et al., 2005; Bonnefond et al., 2010; Lara et al., 2018; Reteig et al., 2019). P1 amplitude was larger for hits than misses, an ERP effect that has been associated with a correct visual detection of infrequent targets (Boksem et al., 2005; Groot et al., 2021; Reteig et al., 2019). Most importantly, the decrement in hits was accompanied by a decrease in N1 and an increase in P3 and SP across time-on-task. Previous evidence is both scarce and inconsistent regarding ERPs associated with the executive vigilance decrement, as either increased (Lara et al., 2018), decreased (Boksem et al., 2005), or similar (Reteig et al., 2019) N1 across time-on-task has been reported. Moreover, while in Lara et al. (2018) P3 decreased across time-on-task, in Bonnefond et al. (2010) late P1 rather increased across blocks. Late ERPs (i.e., as P3 or late P1) changes across time-on-task have received diverse interpretations by resources theories: while a decrease in amplitude has been proposed as a marker of resource depletion with time-on-task (Lara et al., 2018; Warm et al., 2008), increased amplitude has been associated with increased effort to keep resources allocation on the external task (Bonnefond et al., 2010; Koelega et al., 1992).

Nowadays, there is an open debate regarding what ‘attentional resources’ are at the neural level and which neural markers might be indicating a change in resources disposition as a function of time-on-task (Neigel et al., 2020; Thomson et al., 2016). While the present outcomes follow those observed by Bonnefond et al. (2010), we acknowledge that further research is still necessary to elucidate whether P3 and SP increase across time-on-task can be associated with increased effort and resources allocation on the external task. To further understand the implications of neural changes in the vigilance decrement phenomenon, future research should also examine whether changes in ERPs across time-on-task can be associated with changes in sensitivity and/or response bias (Mazzi et al., 2020). In the present study, the decrease in hits was accompanied by a decrease in false alarms [F (3.37, 117.82) = 3.90, p = .008, η_p^2 = 0.10, (0.02, 0.16)], which led to a loss in sensitivity [F (4.51, 157.91) = 3.47, p = .007, η_p^2 = 0.09, (0.01, 0.15)] as well as a change in response bias toward a more conservative criterion [F (4.10, 143.49) = 5.69, $p < .001$, η_p^2 = 0.14, (0.05, 0.21)]. To specifically examine ERPs associated with sensitivity or response bias, future studies might modulate response bias by instructing participants toward a more conservative criterion, as in Mazzi et al. (2020), or modulate sensitivity by reducing the perceptual salience of the infrequent target.

For arousal vigilance, while no significant change across time-on-task was observed in mean RT and early ERPs, N1 and P2 in occipital channels were larger in trials with fastest than slowest RT. Fastest and slowest RT are two of the most used scores to assess arousal vigilance states with the Psychomotor Vigilance Test (Basner & Dinges, 2011). Previous studies have demonstrated that BOLD signal (Drummond et al., 2005) and theta, alpha, and beta power (Molina et al., 2019) also change as a function of the speed of responses in the Psychomotor Vigilance Test. In the present study, differences in P1 and N2 for fastest and slowest responses may be confounded by differences in the speed of response in each set of trials. However, note that P1 and N2 are in the same latency from target onset for fastest and slowest RT trials (see Figure 7). Most importantly, as depicted in Figure S3, P1 and N2 peaks for intermediate RT responses are between peaks for fastest and slowest trials but in the same latency. Therefore, we consider that differences in P1 and N2 for arousal vigilance can be mainly interpreted as differences in ERPs' peaks and not in the response itself.

Importantly, arousal vigilance loss was associated with changes in ERPs similar to those reported by Hoedlmoser et al. (2011), who observed a decrease in early ERPs amplitude after a night of sleep deprivation and measured arousal vigilance with the Psychomotor Vigilance Test. Note that, in Hoedlmoser et al., ERP latency was closer to target onset than in the present study, probably because the millisecond counter was the only stimuli expected. In contrast, in the ANTI-Vea, participants were completing three simultaneous subtasks, all with different target stimuli. Previous research has reported changes in ERPs associated with arousal vigilance loss in repeated sessions during a night (Hoedlmoser et al., 2011; Ramautar et al., 2013) or even weeks (Witkowski et al., 2015). In the present study, we demonstrated that changes in ERPs associated with arousal vigilance loss (i.e., fastest vs. slowest responses) can be observed within a single session of ~38 min.

It is important to note that the present study is not exempt from some methodological limitations, which have been partially addressed with our data but should be considered in future studies. As described in Section 2.3, trials with vertical eye movements between the visual cue and the target could not be excluded. Vertical eye movements after the visual cue could have created artificial differences between valid and invalid conditions in ERPs of interest for the orienting network. However, as depicted in Figure S1, a similar baseline (i.e., the trial period wherein visual cue is presented) for valid/invalid and no cue trials was observed. While vertical eye movements could have influenced ERPs waves in P1 and N1 in occipital channels, note that P3 wave was similar between valid/invalid and no cue trials, that is, wherein no vertical eye movements should have occurred (see Figure S1).

Moreover, in the ANTI-Vea, the SOA between the visual cue and the target is relatively short (100 ms), which limits the interpretation of ERPs associated with the orienting effect as changes evoked by the target stimuli. Considering this limitation, ERPs associated with the orienting network were instead discussed as signal modulation by the validity condition in the time window of each ERP of interest. The effect of visual cue on ERPs seems to be relatively small, as demonstrated by the similar baseline between no cue and invalid/valid conditions in Figures S1 and S2. The visual cue could have distorted P1 and N1 in occipital channels, but not P3 in central-parietal channels, wherein the wave was similar between valid/invalid and no cue trials (see Figure S1). However, note that in the present study P1 and N1 were observed as in previous studies with attentional networks tasks, either with a similar procedure (Abundis-Gutiérrez et al., 2014) or with a larger SOA between the visual cue and target (Gonçalves et al., 2018). Future studies with the ANTI-Vea should consider this critical aspect of the task when interpreting outcomes associated with cueing validity or even modify the SOA between visual cue and target to avoid potential distortion effects by the visual cue on ERPs associated with the orienting network.

In addition, the arousal vigilance decrement in mean RT usually reported with the ANTI-Vea was not observed here (Luna, Roca, et al., 2021). Similarly, in a previous study wherein participants completed the ANTI-Vea, while anodal/sham transcranial direct current stimulation was delivered and EEG signal was recorded, the decrement in mean RT for arousal vigilance was not observed (Luna et al., 2020). Indeed, in the present data, the arousal vigilance decrement was also not significant for SD of RT, [F (1, 35) = 0.60, p = .658, $\eta_p^2 = 0.02$, (0.00, 0.03)]. Although the lack of behavioral decrement could be a limitation for analyzing ERPs associated with arousal vigilance loss, other typical scores describing arousal vigilance states in single RT tasks could be computed in the present study, that is, fastest and slowest RT (Basner & Dinges, 2011; Molina et al., 2019). Finally, different proportions of hits and misses were observed in the present study (see Table 3). Following Cohen (2014), differences in the N of trials between conditions are particularly problematic for phase-based and amplitude-based analyses, and should be particularly observed for ERPs when the N of trials is below 30 in any condition (see in Table 3 that the mean N of misses per participant is ~60). Indeed, anticipating this issue, in the present study participants completed two repeated sessions, thus increasing the N of trials in executive and arousal vigilance measures.

To conclude, the present study shows that different ERPs associated with attentional networks can be simultaneously observed within a single session, adding independent measures of executive and arousal vigilance within the alerting network (Luna et al., 2018; Petersen & Posner, 2012; Posner, 2008). Similar ERPs to those previously observed by Abundis-Gutiérrez et al. (2014) were found here, in particular: (a) for phasic alertness, warning signal elicited early ERPs as N1 and P2 as well as a CNV preceding the target; (b) for the orienting network, cueing validity did not modulate P1 and N1 and, in contrast to Abundis-Guitiérrez et al., cueing validity did not modulate P3; (c) for the executive control network, congruency modulated N2 for conflict detection and SP for conflict resolution. Importantly, different ERPs were simultaneously observed for independent measures of executive and arousal vigilance. Although the executive vigilance decrement was accompanied by an increase in P3 and SP amplitude, reduced arousal vigilance was associated with a decrease in N1 and P2. The present study demonstrates that attentional networks can be measured by changes in different ERPs simultaneously observed in a single session (Luna et al., 2018; Petersen & Posner, 2012; Posner, 2012; Posner et al., 2006).

AUTHOR CONTRIBUTIONS

Fernando Gabriel Luna: Conceptualization; data curation; formal analysis; investigation; methodology; resources; software; validation; visualization; writing – original draft; writing – review and editing. **María Julieta Aguirre:** Conceptualization; data curation; formal analysis; investigation; methodology; software; validation; visualization; writing – review and editing. **Elisa Martín-Arévalo:** Conceptualization; formal analysis; methodology; software; supervision; validation; writing – review and editing. **Agustín Ibáñez:** Conceptualization; resources; software; validation; writing – review and editing. **Juan Lupiáñez:** Conceptualization; formal analysis; methodology; project administration; software; supervision; validation; writing – review and editing. **Pablo Barttfeld:** Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

All authors disclose any potential sources of conflict of interest on this submission.

DATA AVAILABILITY STATEMENT

The methods and analysis of the current study are available in the Open Science Framework repository, https://osf.io/6kc7x/. Data supporting the conclusions of this study will be made available on request to Fernando G. Luna (fluna@unc.edu.ar) and Pablo Barttfeld (pablob@conicet.gov.ar).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Figure S1-S3

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