

A systematic exploration of attentional load effects on the C1 ERP component

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Abstract

The C1 ERP component reflects the earliest visual processing in V1. However, it remains debated whether attentional load can influence it or not. We conducted two EEG experiments to investigate the effect of attentional load on the C1. Task difficulty was manipulated at fixation using an oddball detection task that was either easy (low load) or difficult (high load), while the distractor was presented in the upper visual field (UVF) to score the C1. In Experiment 1, we used a block design and the stimulus onset asynchrony (SOA) between the central stimulus and the peripheral distractor was either short or long. In Experiment 2, task difficulty was manipulated on a trial-by-trial basis using a visual cue, and the peripheral distractor was presented either before or after the central stimulus. The results showed that the C1 was larger in the high compared to the low load condition irrespective of SOA in Experiment 1. In Experiment 2, no significant load modulation of the C1 was observed. However, we found that the contingent negative variation (CNV) was larger in the low compared to the high load condition. Moreover, the C1 was larger when the peripheral distractor was presented after than before the central stimulus. Combined together, these results suggest that different top-down control processes can influence the initial feedforward stage of visual processing in V1 captured by the C1 ERP component.

KEYWORDS

attentional load, C1, CNV, EEG, working memory

1 | INTRODUCTION

Whether selective attention as a high-level factor can modulate visual processing at the earliest cortical stage in the occipital lobe has been debated for decades (Baumgartner et al., 2018; Rauss et al., 2011; Slotnick, 2018). Studies using single-cell recording in monkeys have demonstrated that neural activity in the lateral geniculate nucleus (LGN) and V1 can be affected by attention (Chen et al., 2008; Hembrook-Short et al., 2018; Motter, 1993; O'Connor et al., 2002; Shah et al., 2022). Earlier functional magnetic resonance imaging (fMRI) research has also shown that

attention can influence primary visual cortex (V1) activity (Gandhi et al., 1999; Hopf et al., 2004; Somers et al., 1999). However, due to the low temporal resolution of fMRI, it remained difficult to attribute this modulation in V1 either to an initial feedforward effect from the retino-geniculostriate pathway or instead, a delayed reentrant feedback effect from the extrastriate cortex (Hillyard & Anllo-Vento, 1998). In contrast to fMRI, electroencephalography (EEG) provides an excellent temporal resolution, allowing to track brain activity using a millisecond time scale and scrutinize the fast temporal dynamics of complex cognitive processes such as attention. The C1 ERP component,



which is the first cortical visual evoked potential following stimulus onset, reflects the earliest cortical activity originating in V1 (Clark et al., 1994; Di Russo et al., 2002, 2003; Foxe et al., 2001; Jeffreys & Axford, 1972). Sometimes, it is also termed the N/P80 component (Proverbio & Adorni, 2009; Proverbio et al., 2010, 2021) as it usually peaks 70–80 ms after stimulus onset and shows a negative polarity when the stimulus is presented in the UVF but a positive polarity when presented in the lower visual field (LVF). This polarity reversal is compatible with the cruciform model of striate generation of the C1 ERP activity (Di Russo et al., 2003, 2005; Jeffreys & Axford, 1972). Moreover, the extrastriate P1 component which follows the C1 can also exhibit polarity inversion for UVF versus LVF presentations (Ales et al., 2010, 2013). However, it is expressed in the opposite direction compared to the preceding C1 (Bayer et al., 2017; Kelly et al., 2013; Rauss et al., 2009; Rossi & Pourtois, 2012, 2017; Vanlessen et al., 2012, 2014). As such, the C1 has been used as a valid electrophysiological correlate of V1 processing, which can be harnessed to noninvasively explore possible modulations of attention or other cognitive factors on early visual processing in V1 in humans (Foxe et al., 2008; Foxe & Simpson, 2002; Gomez Gonzalez et al., 1994). Through the years, several studies have investigated the effects of spatial attention, feature-based attention, and object-based attention on the C1, often with mixed results reported (see Brockhoff et al., 2022; Slotnick, 2018 for reviews). While some studies, especially recent ones, found evidence for attentional modulation of the C1 (Fu et al., 2009; Kelly et al., 2008; Proverbio et al., 2010, 2021; Rauss et al., 2009; Rossi & Pourtois, 2012; Zani & Proverbio, 2018, 2020), or even the N40 that precedes it (Proverbio et al., 2021), other studies did not, and argued instead for a delayed feedback effect in V1 from extrastriate visual areas, as captured by the subsequent P1 component showing modulations by (spatial) attention (Di Russo et al., 2003; Martínez et al., 1999). Recently, we systematically reviewed these studies and conducted a meta-analysis involving 47 experiments and 794 participants in total. Despite the discrepancy among the results, a moderate effect on the C1 was found, indicating a modulation of attention in the earliest vision stage (Qin et al., 2022).

In recent years, a growing body of research has examined the modulatory effects of attention on vision by adopting a different approach and embracing a different theoretical framework, namely the perceptual load theory (Forster & Lavie, 2008; Lavie, 1995; Lavie & Tsai, 1994). According to it, if the task requires low perceptual load (i.e., it can be solved using few attentional resources), then the distractibility is increased because the attentional resources can spill over to irrelevant stimuli. In contrast, if the task requires high perceptual load (i.e., more

attentional resources are consumed by it), distractors can more easily be filtered out, and hence, they eventually produce less interference compared to the low load condition. Usually, changes in perceptual load are achieved by varying the amount of stimuli (or distractors) to be processed at the same time (Lavie, 1995; Lavie & Tsai, 1994). In comparison, changes in attentional load are obtained by keeping the visual input constant between conditions, but varying task demands based on it (Brockhoff et al., 2022; Wolf et al., 2022), for example, by asking participants to perform either simple detection or conjunction search (Herde et al., 2022; Rauss et al., 2009, 2012), or passive viewing versus active task (Fu et al., 2010b). Hence, although perceptual load and attentional load likely share some common ground (i.e., more attention resources are allocated in the high than low load condition), they can be dissociated from each other at the methodological level. Moreover, it is important to note that spatial attention is yet another family of attentional control effects. Changes in spatial attention are usually achieved by the use of visual cues, which can be either compatible (valid trials) or incompatible (invalid trials) with the subsequent target's location (Baumgartner et al., 2018; Di Russo et al., 2003; Kelly et al., 2008). In comparison, in studies on attentional load and perceptual load, participants are asked to attend to a central task-relevant stimulus while ignoring peripheral task-irrelevant distractors. In a recent ERP study, Wolf et al. (2022) compared the effects of attentional load, spatial attention, and task relevance on the C1 and P1 components, and found evidence for their modulation by spatial attention, but not by the two other attention control processes. However, in our recent meta-analysis (Qin et al., 2022), we found that both attentional load and spatial attention influenced the C1 component, as shown by a larger amplitude for low than high load condition, but also for valid than invalid trials.

When focusing on attentional load, several previous fMRI studies have demonstrated a significant impact of attentional load on the visual cortex, including in V1, as evidenced by changes in blood oxygen level dependent (BOLD), namely reduced visual processing of the distractor in the high compared to the low load condition (Bahrami et al., 2007; O'Connor et al., 2002; Rees et al., 1997; Schwartz et al., 2005). Moreover and importantly, several EEG studies documented that this effect could also be traced at the level of the C1 component, showing a lower amplitude for the high compared to the low load condition (Rauss et al., 2009; Rossi & Pourtois, 2012, 2014, 2017). These neurophysiological findings lent support to the notion that attentional load can gate the earliest stage of cortical processing in V1. Nevertheless, other EEG studies have not found significant modulations of the C1 as a function of attentional

load, even though some of them used a similar experimental design and implementation of attentional load (Ding et al., 2014; Fu et al., 2012; Wolf et al., 2022). For example, Ding et al. (2014) used a perceptual discrimination task at fixation with two levels of load, while peripheral distractors were shown in the UVF, in keeping with Rauss et al. (2009). They increased the signal-to-noise ratio (by increasing the number of trials) and removed the potential overlap from previous ERP components that might contaminate the C1. Unlike Rauss et al. (2009), they reported no statistically significant effect of attentional load on the C1.

These ERP results were puzzling, and at present, it remains unclear what could be the source(s) of these inconsistent findings. There may be several methodological factors that could potentially explain the discrepancy, including the scoring method used for the C1 and the actual operationalization of attentional load. Moreover, as discussed by Slotnick (2018), there is substantial variability in the anatomy of V1 and the calcarine fissure across participants. Some slight changes in the stimulus or task parameters might also have a profound influence on the C1, and eventually its modulation by attention (Fu, 2018; Herde et al., 2020). For example, a recent ERP study showed that increasing attentional load at fixation reduced the C1 elicited by the peripheral distractors in the LVF but not in the UVF (Herde et al., 2022). This is opposite to what has been found in several previous studies where modulation of the C1 was mostly found in the UVF (Pourtois et al., 2008; Rauss et al., 2009, 2012).

A methodological factor that has not been considered yet in these existing studies is the length or duration of the stimulus onset asynchrony (SOA) between the central stimulus and the peripheral distractor. In previous ERP studies on attentional load, a gap was usually introduced between the central task-relevant stimulus and the peripheral task-irrelevant distractor (i.e., SOA of 500–750 ms in Herde et al., 2022; SOA of 500–743 ms in Rauss et al., 2009; SOA of 500–750 ms in Rossi & Pourtois, 2012, 2017). Although the SOA varied in these earlier studies, they did not directly compare short to long SOAs. However, modulatory effects of attention on the C1 (for the peripheral distractor) could be transient and hence depend on attention allocated to the central stimulus. If the gap between these two stimuli or events is too long or suboptimal, then attentional load could presumably not influence the C1 ERP component easily due to less attentional competition created in turn. The temporal feature of attention allocation has been investigated in a wealth of studies (Nobre et al., 2007, 2014; Nobre & Van Ede, 2017). SOA was found to play a critical role in the variability and strength of the attentional effects observed, such as the attention blink (Dux & Marois, 2009; Shapiro et al., 1997) in rapid serial

visual presentation (RSVP) tasks or the attention orienting versus disengagement effect in Posner's cueing paradigms (Posner, 1980). Moreover, Rauss et al. (2012) previously used a design similar to Rauss et al. (2009) but presented the peripheral distractor and central stimulus simultaneously (whereas a gap was used in Rauss et al., 2009). Strikingly, they found an inverse load effect for the C1: It was larger for the high compared to the low load condition, which was opposite to what Rauss et al. (2009) found. These results suggested more processing in V1 in the high compared to the low load condition, when the peripheral distractor was shown concurrently with the central stimulus. This finding was tentatively interpreted as reflecting a possible temporal grouping between the central stimulus (where the load was imposed) and the peripheral distractor (Blake & Lee, 2005). More specifically, due to their simultaneous onset, not only the central stimulus but also the peripheral distractor benefited from more attention in the high compared to the low load condition, which in turn enhanced the processing of the peripheral distractor at the C1 level. Although this interpretation awaits confirmation at the empirical level, these results, together with those of Rauss et al. (2009), indirectly suggested that variations in the relative timing between the central stimulus and peripheral distractor could have a significant impact on the attentional load effect observed at the C1 level. In light of this evidence, we sought to further assess in a new EEG experiment the possible modulatory role of the SOA between the central stimulus and the peripheral distractor (i.e., temporal attention) for effects of attentional load on the C1. This was the main goal of Experiment 1. More precisely, in keeping with these previous ERP studies on attentional load reviewed here above, we introduced a gap between the central stimulus and the peripheral distractor. In some blocks, the SOA was set to 450–600 ms (i.e., short SOA), while in others, it was set to 900–1050 ms (i.e., long SOA). We hypothesized that in the high load condition, the C1 should be reduced for the peripheral distractor compared to the low load condition, especially when a short SOA would be used because attention competition would increase in this condition. As a result of it, a push-pull mechanism could operate in the high load condition (Pinsk et al., 2004), whereby the distractor (i.e., the peripheral distractor) is actively “pushed away” or suppressed to reduce the competition with the task-related stimulus (i.e., the central stimulus). In comparison, for the long SOA, attention competition could be reduced because the distractor is shown at a time when the central stimulus is expected to be fully processed. Hence, for the long SOA condition, the C1 should be comparable in the two load conditions. In other words, we expected a significant interaction effect between SOA and attentional load for the C1 amplitude.

Besides the SOA, another important methodological factor is the type of experimental design and hence the actual operationalization of attentional load, achieved using either a block or event-related design. In previous EEG studies (Rauss et al., 2009; Rossi & Pourtois, 2012), a block design was used. Although block designs provide an adequate signal-to-noise ratio and have been used extensively in early neuroimaging studies (Amaro & Barker, 2006; Bandettini, 1993; Dale & Buckner, 1997; Donaldson, 2004; Petersen & Dubis, 2012), they also have some disadvantages, including fluctuations in sustained attention. More specifically, they can sometimes lead to vigilance decrement (Parasuraman, 1979; Parasuraman & Davies, 1977; Parasuraman & Mouloua, 1987). This phenomenon was initially demonstrated in an experiment by Mackworth (1948), who found that the ability to observe rarely presented targets declined significantly over time. Back then, two dominant theories were proposed regarding this phenomenon. The first one was the resource depletion account, which assumes that since the total attentional resources decline over time, attention allocated to the task also decreases gradually (Thomson, Besner, & Smilek, 2015; Thomson, Smilek, & Besner, 2015; Warm et al., 2008). The other theory, called the mindlessness account, assumes that repetitive and/or monotonous responses to targets are under-stimulating and cause disengagement from the task (Robertson et al., 1997; Smallwood et al., 2004). Many studies have investigated those two models using vigilance tasks and more specifically the sustained attention to response task (SART; Helton, 2008; Helton et al., 2005; Robertson et al., 1997; Temple et al., 2000). However, there was also evidence showing that this decrement can be alleviated by varying task demands or inserting warning cues prior to the target stimulus (Maclean et al., 2009; Thomson, Smilek, & Besner, 2015).

In light of this evidence, we could argue that a block manipulation of attentional load could be suboptimal for creating a stable and robust top-down attention control effect on the C1 ERP component. As a corollary, a trial-by-trial manipulation of attentional load could be more appropriate for the C1 ERP component and reveals stronger effects on it. Moreover, we could easily achieve a trial-by-trial change of attentional load by including a specific visual cue prior to each trial and informing the participants about the load level in the upcoming trial (Schevernels et al., 2014). Interestingly, when using EEG methods, we could also look at specific ERP components elicited by this visual cue, including the Contingent Negative Variation (CNV), which is a slow, negative potential evoked during the interval between a warning cue and a subsequent imperative stimulus (Leynes et al., 1998; Mento, 2013; Walter et al., 1964). This ERP component is closely related to

anticipation and preparatory attention. Hence, we could record and analyze this ERP component to assess the extent to which participants would differentially prepare for the following low versus high load trial. To the best of our knowledge, while a trial-by-trial manipulation has already been used in the past to examine the effects of perceptual load on the C1 (Fu et al., 2009, 2010a), it has not been applied yet to investigate the effects of attentional load on this early visual component (or later ERP components). The goal of Experiment 2 was to fill this gap and assess whether the C1 ERP component could be influenced by attentional load when this manipulation was achieved using an event-related design and specific cueing technique.

To this aim, we employed a new design in Experiment 2, in which the level of attentional load, either low or high, randomly varied across successive trials. Moreover, we also presented the peripheral distractor either prior to or following the central stimulus, to explore whether during task preparation (i.e., following the cue), a significant load effect on the C1 could already be found or it was restricted to the post-central stimulus interval only. We expected a more negative CNV in the high compared to the low load condition, which would suggest a stronger anticipation or preparation in the former compared to the latter condition. As for the C1 in response to the peripheral distractor, we hypothesized it to be smaller in the high compared to the low load condition. However, we did not have specific theoretical or methodological reasons to expect this load effect, should it be found eventually, to be stronger for the pre- or the post-central stimulus interval.

2 | EXPERIMENT 1

2.1 | Materials and methods

2.1.1 | Participants

Twenty-nine healthy adults participated in this experiment. Although we did not perform an a priori power analysis, we aimed at including as many participants as Rossi & Pourtois (2012, $N=25$; 2014, $N=26$), where effects of attentional load on the C1 were reported using a similar task. They were recruited via SONA, which is an online system at Ghent University. They gave written informed consent. They all had normal or corrected-to-normal vision, without any reported neurological or psychiatric disease or treatment. The experiment was approved by the local ethics committee of the Faculty of Psychology and Educational Sciences, Ghent University. Three subjects were excluded from further analyses because of low behavioral performance (i.e., one subject had a low hit rate in the low load and short SOA condition: $M=69.44%$; two

others made a lot of false alarms: $M = 17.36\%$ and 15.97%). Two other subjects were excluded as well due to the lack of a clear C1 ERP component. Thus, the final sample consisted of 24 subjects (aged 19–34, mean age = 23.33 years, $SD = 4.17$ years, five males).

2.1.2 | Apparatus

Participants were seated in an electrically shielded and soundproof room with dim lights, 63 cm away from the computer screen. Head movements were restrained by a chin rest, which was also used to facilitate eye tracking. Stimuli were generated with Psychtoolbox-3 (Brainard, 1997; Pelli & Vision, 1997) running on MATLAB R2019a (The MathWorks, Inc.) and presented on a 19' inch CRT monitor (1600×1200 resolution at 75 Hz). Responses were recorded using a standard computer keyboard. Eye movements were monitored monocularly using an SR Research Eyelink 1000 Plus system (SR Research Ltd.) at a sampling rate of 1000 Hz. EEG data were recorded continuously using a 64-channel BioSemi Active Two system (BioSemi). The sampling rate was 512 Hz and the CMS-DRL electrodes were used as online reference. The electrooculogram (EOG) was recorded from four external electrodes placed on the outer canthi (to monitor horizontal eye movements) and above and below the left eye (to monitor eye blinks). Two other electrodes were placed on the left and right mastoids, which were used off-line for re-reference.

2.1.3 | Stimuli and task

To study modulatory effects of attentional load on early visual processing, we used an oddball detection task at fixation with which target discrimination could be either easy in some blocks (low load) or difficult in others (high load). Participants were shown a series of visual stimuli where they had to signal by keypress the detection of a predefined deviant target that was embedded in a series of standard stimuli for which no response was required. The standard stimulus was a small line bar oriented 35 degrees clockwise. It appeared in 4/5 of the trials. The target, presented in only 1/5 of the trials, was a small line bar whose orientation was different from the standard, either 42 or 47 degrees tilted clockwise, corresponding to the high and low load, respectively. As a result of this change in task difficulty regarding the discrimination of the target relative to the standard stimulus, attentional load was either low or high. A larger angular difference between them led to an easy discrimination task, while a smaller angular difference led to more difficult one. In analogy with previous

EEG studies that have already used this same task difficulty manipulation in the past (see Section 1), we refer to its effects on visual processing at the behavioral and ERP levels as attentional load.

All stimuli were presented in white on a screen with a black background. A central dot was shown throughout the block to ensure fixation. Each trial started with a fixation screen (blank interval) shown for 250 ms. Following it, a central stimulus, either the standard or the target (subtending 1.3 degrees), was presented 0.3 degrees above this central dot for 250 ms. Participants were required to press the space key as quickly as possible when they detected the deviant orientation. No response was required for the standard stimulus. After the onset of the central stimulus, either a short (450–600 ms) or long (900–1050 ms) interval was used, before an array of stimuli (7.4×30 degrees) consisting of 6×24 slightly jittered bars (horizontally oriented) could be presented for 150 ms in the UVF, with its lower edge being located 6 degrees above the central fixation dot. This array of stimuli shown in the UVF served as the peripheral distractor. Based on previous ERP studies (Rauss et al., 2009; Rossi & Pourtois, 2012), we expected it to elicit a clear C1 component (with a negative polarity given the position in the UVF; see Jeffreys & Axford, 1972). This peripheral distractor was presented in 1/3 of the trials only, making its occurrence low and unpredictable. In the remaining 2/3 of the trials, no distractor was shown. We called these events (no distractor shown in the UVF) *dummies*. We used them to compute a baseline ERP activity against which visual ERPs elicited by the distractor (including the C1) could be compared/subtracted. This way, we could remove the possible contribution of overlapping ERP components evoked by the preceding central stimulus (see data analyses here below). The trial ended with a fixation screen (blank screen) shown for 150–250 ms (see Figure 1).

2.1.4 | Procedure

The experiment consisted of four parts, namely practice, main session, localizer, and awareness assessment.

After EEG preparation, participants were seated in the testing room and received instructions about the task to perform and the visual stimuli that they would encounter. They first completed a practice block (30 trials) in which attentional load was set to a low level while the short and long SOAs were used in random order.

For the main session, two experimental factors, namely attentional load (either low or high) and SOA (either short or long) were manipulated using a block design. Hence, they were four experimental conditions in total. Their order was counterbalanced across

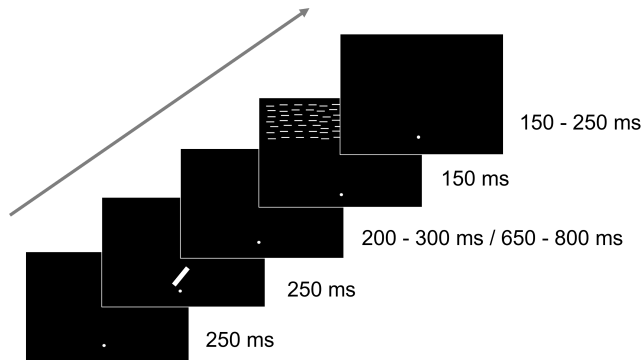


FIGURE 1 Trial structure. After a 250 ms fixation display, the central stimulus (either the standard or the target) was presented for 250 ms. Participants were required to report the deviant orientation (target) by pressing the space bar. Following the central stimulus, either a short (200–350 ms) or a long interval (650–800 ms) was used to yield either a short (450–600 ms) or long SOA (900–1050 ms) between the central stimulus and the peripheral distractor. After this interval, the distractor could be shown in the UVF for 150 ms. The trial ended with a fixation display that lasted for 150–250 ms.

participants. Specifically, four specific orders were used: LS-LL-HS-HL, LL-LS-HL-HS, HS-HL-LS-LL, or HL-HS-LL-LS. LS refers to low load and short SOA, LL to low load and long SOA, HS to high load and short SOA, and HL to high load and long SOA. Each condition included two successive blocks, thus participants were required to complete eight blocks in total. Each block comprised 90 trials, subdivided into 18 targets and 72 standard stimuli. Trial order in each block was pseudorandom. Prior to the start of each block, both the standard and the target were presented on the screen to inform participants about the (angular) difference between them and hence the difficulty level to be expected (either easy/low load or difficult/high load). Then, the calibration of the gaze position was performed using a standard nine-point calibration procedure. During each block, participants were asked to limit (body) movements and keep fixation on the central dot. Short breaks (lasting a minimum of 1 min) were included in between blocks. On average, participants rested ~2 min before resuming the task in a new block.

In addition, participants performed an additional localizer run containing four blocks of 90 trials each (corresponding to LS, LL, HS, and HL). Two of them were completed before the main session and two others after it. They were similar to the main task, except that the peripheral distractor was randomly presented either in the UVF or lower visual field (LVF). This localizer run was used to compute the C1 component using independent ERP data (relative to the main session) and ascertain that it showed the expected polarity reversal depending on the position

of the stimulus (peripheral distractor) in the visual field (Rossi & Pourtois, 2012).

At the end of the experiment, three questions were asked to assess participants' awareness of the SOA manipulation: (Q1) In some blocks, the time interval between the central bar and the peripheral bars was short. In other blocks, it was longer. Did you notice that? [Yes/No]; (Q2) In which condition was it easier to ignore the peripheral bars? If you did not notice any difference, just guess. [Short/Long]; (Q3) Regarding the second question, how confident are you about the feeling? [Very confident/A little/Not so confident/Not at all]. Participants responded to these questions using the mouse.

2.1.5 | Statistical analyses

Behavioral data

Data analyses were conducted with MATLAB R2017a (The Mathworks Inc.) and JASP 0.17 (JASP Team, 2023). Hit rate, false alarm rate, and mean reaction time (RT) for correct responses were computed for each experimental condition and each participant. When computing the mean RTs, for each participant separately, those trials in which the RTs exceeded three standard deviations above or below the condition-specific mean were excluded. We also excluded participants whose mean hit rate, mean false alarm rate, and mean RTs exceeded three standard deviations above or below the condition-specific mean of all subjects. Repeated-measures ANOVAs with load and SOA as within-subject factors were conducted for each of these dependent variables.

Awareness of SOA manipulation

For the first question, we calculated the percentage of participants who were aware of the SOA manipulation. Likewise, for the second question, we calculated the percentage of participants who found the short versus long SOA condition easier. We also computed the mean and standard deviation across the four response options for the third question.

EEG preprocessing

EEG data preprocessing was implemented with the EEGLAB toolbox (Delorme & Makeig, 2004) running on MATLAB R2017a (The Mathworks Inc.). First, the data were filtered with a 0.1-Hz high-pass and a 40 Hz low-pass finite response filter with default settings and referenced to the average of the left and right mastoids. A high-pass filter at 0.1 Hz was demonstrated not to distort the EEG signal (Tanner et al., 2015). Then, the EEG was synchronized together with the eye-tracking data using the EYE-EEG toolbox (Dimigen et al., 2011). After synchronization,

TABLE 1 Average number of epochs included in the averaging after preprocessing, for each stimulus type separately.

	Distractor	Target	Standard stimulus
Low load & Short SOA	40.17 (5.87)	19.96 (3.51)	88.00 (3.90)
Low load & Long SOA	42.46 (2.21)	20.58 (3.43)	88.04 (4.04)
High load & Short SOA	40.50 (3.53)	20.38 (3.20)	86.83 (4.04)
High load & Long SOA	38.96 (5.21)	21.13 (1.68)	86.54 (4.09)

Note: Before preprocessing, 48 trials were retrieved for the peripheral distractor for each condition; for the target, 24 trials were retrieved for each condition; for the standard stimulus, 96 trials were retrieved for each condition. Standard deviation is shown in parentheses.

we computed the joint probability for the continuous data at each electrode. The channels whose data's joint probabilities exceeded a threshold of three standard deviations from the mean probability were marked and subsequently interpolated. Next, we extracted two epochs of interest: The first one was $-110/+700$ ms around the central stimulus onset. The second one was $-110/300$ ms around the onset of the peripheral distractor (or dummies in a separate condition) in non-target trials and no response in the preceding 1100 ms time interval was recorded. Because the SOA between the central stimulus and the peripheral distractor was either 450–600 ms (short SOA) or 900–1050 ms (long SOA), we used a long interval for the second epoch (encompassing a long interval prior to stimulus onset) such that epochs contaminated by motor responses (to the preceding central stimulus) could be identified and removed based on the corresponding response-related trigger. For the second type of epoch, we also removed epochs in which the distractor followed a central target as their processing was probably contaminated and/or they contained overlapping ERP components from the target. After this step, we re-epoched them using a $-110/+300$ ms interval. Individual epochs were baseline-corrected using the 100 ms pre-stimulus onset interval. Then, for each type of epoch, we used the FASTER plugin (Nolan et al., 2010) to further identify artifacts along five dimensions: (1) Channels whose mean correlation coefficient, variance, and Hurst exponent exceeded $Z = \pm 3$ were removed and data at these electrodes were interpolated; (2) epochs in which the amplitude range, the deviation from the channel average, and the variance exceeded $Z = \pm 3$ were rejected; (3) some small artifacts might only exist on single channels within single epochs. Therefore, within each epoch, channels whose variance, median slope, amplitude range, and the deviation from the channel average exceeded $Z = \pm 3$ were interpolated using spherical splines; (4) a grand average dataset was then established. For each subject, if the amplitude range, variance, deviation from the channel average, and the maximum absolute value of the EOG channels exceeded $Z = \pm 3$ of the grand average, the subject's data were entirely removed; (5) epochs with more than 12 interpolated electrodes were directly

removed. In addition, we conducted Kurtosis analysis to remove epochs with abnormal peak values ($Z > 5$) and performed Spectra Estimate to reject epochs with muscle activity (i.e., the trial spectra deviated by $+25$ or -100 dB in the 20–40 Hz frequency window). Furthermore, independent components (ICs) analyses were performed and ICs related to eye blinks and movements were detected, and manually rejected based on visual inspection of the EEG and eye-tracking data. We also removed epochs in which participants blinked or their gaze deviated more than 2.5 degrees from central fixation (cf. dot's location; see Figure 1) during the presentation of the distractor (or dummies). Table 1 shows the average number of epochs kept for each condition in the last.

EEG data from the localizer run were preprocessed following the same steps. We epoched the data around the onset of the distractor and computed visual ERPs separately for the UVF versus LVF.

ERPs

The quantification of the ERP components was in accordance with the previous ERP studies (Rauss et al., 2009; Rossi & Pourtois, 2012).

For the peripheral distractor, we computed two ERP components, namely the striate C1 and the extrastriate P1. Based on the results of previous studies (Rauss et al., 2009, 2012) and the topographical properties of the current ERP data set, the C1 was identified as the most negative peak present around 50–100 ms after stimulus onset at electrodes CPz, Pz, and POz. We used the data from the localizer run to determine the latency of the C1 (for peripheral distractor shown in the UVF). It was used to identify the C1 in the main session. The mean amplitude of the C1 for the peripheral distractor in the main session was computed in a $-10/+10$ ms interval around this peak latency. For these three occipitoparietal electrodes along the midline, a mean amplitude measurement was used. To remove the potential contribution of overlapping ERP components elicited by the preceding central stimulus, we first computed the ERPs for dummies in each experimental condition (block) and subtracted them from the ERP waveforms computed for

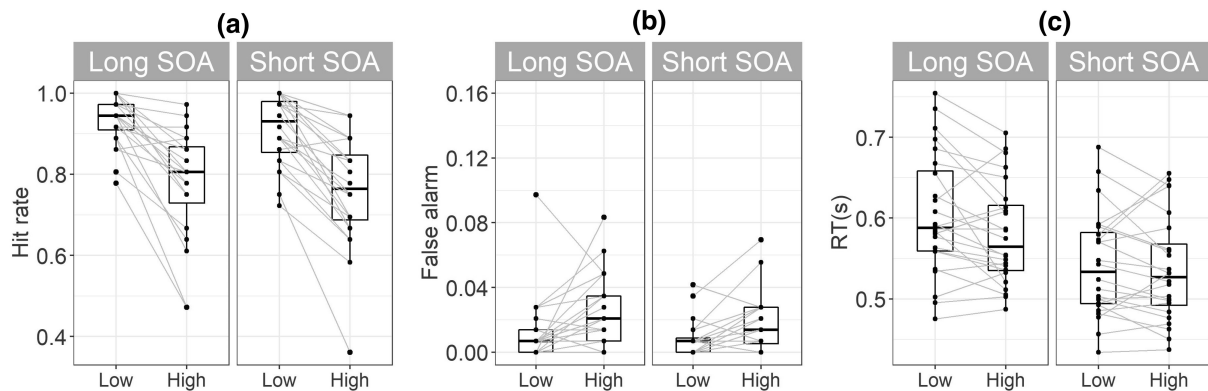


FIGURE 2 The boxplots depict the behavioral results of Experiment 1 for each condition separately. (a) hit rate; (b) false alarm rate; (c) Mean RTs for correct responses. Each point in these boxplots represents an individual subject result, with the connecting lines showing the effect of attentional load for each SOA separately.

the distractor. These “overlap-free” C1 amplitudes were then used for statistical analyses (see also [Supporting Information](#) for the results based on the uncorrected C1 amplitudes). Moreover, we also performed a refined peak measurement of the C1 where we first determined for each subject separately the electrode and latency showing the largest negative amplitude in response to the distractor when collapsing all conditions of the main session. We then scored the amplitude of the C1 (using this subject-specific electrode and peak latency) for each experimental condition separately. The ERP waveforms for the dummies were also subtracted from those for the distractor to remove the contribution of possible overlapping ERP components from the preceding event (see [Supporting Information](#)).

For the subsequent P1 component, which peaked at around 100–150 ms at electrodes O1, Oz, and O2 following distractor onset, we also used a mean amplitude measurement (i.e., 20 ms time window around the peak). The peak latency of the P1 was determined using the ERP data from the localizer run. Mean amplitudes of the C1 and the P1 were each submitted to a repeated-measures ANOVA with load and SOA as within-subject factors.

In addition, we also performed two control analyses for the C1 to remove the potential contribution of overlapping ERP components elicited by the preceding central stimulus (see [Supporting Information](#)). In the first analysis, we computed the mean ERP amplitude during the pre-C1 interval (0–40 ms following stimulus onset) and computed the C1 (using a mean amplitude measurement; see above) relative to it (i.e., we subtracted from the C1 the pre-C1 activity). In the second analysis, for each experimental condition, we first computed the ERPs for dummies. We then subtracted them from the ERP waveforms computed for the distractor and subsequently used the same processing steps as described here above to score and analyze the C1 component. The results of these control analyses on the

C1 were consistent with those of the main analysis and can be found in [Supporting Information](#).

For the central stimulus (either the target or the standard), we scored the P300 ERP component using a mean amplitude measurement at electrodes CPz, Pz, and POz in the 350–550 ms time interval following its onset. Mean P3 amplitudes were submitted to a repeated-measures ANOVA including load, SOA, and targetness as within-subject factors.

For all ERP components, complementary Bayesian repeated-measures ANOVAs were also conducted. Following the suggestion from van den Bergh et al. (2020) and Wagenmakers et al. (2018), we computed the model-averaged results (only considering the matched models), which show the prior and posterior inclusion probabilities and the inclusion Bayes factor (BF_{incl}) for each main effect and interaction. BF_{incl} , which is the change from prior inclusion odds to posterior inclusion odds, can therefore be interpreted as the evidence in the data for including a main effect or interaction. For the interpretation of the BF_{incl} , we used the standard classification table for BF_{10} , as they are similar in the case of simple comparisons (Pertsov et al., 2020; van den Bergh et al., 2020; van Doorn et al., 2021).

2.2 | Results

2.2.1 | Behavioral results of experiment 1

The ANOVA on hit rates ([Figure 2a](#)) revealed a significant main effect of Load ($F_{1,23}=67.574$, $p<.001$, partial $\eta^2=0.746$), showing a higher accuracy in the low than high load condition. Neither the effect of SOA ($F_{1,23}=1.735$, $p=.201$, partial $\eta^2=0.070$) nor the interaction between the two factors ($F_{1,23}=0.022$, $p=.884$, partial $\eta^2=9.398e-4$) reached significance. For false alarms

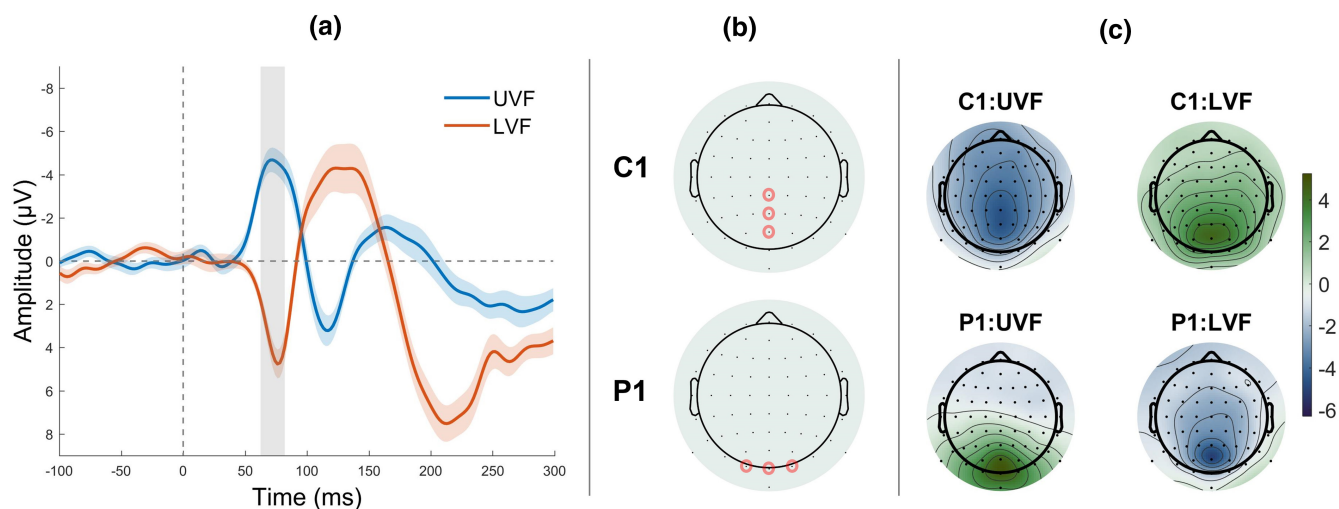


FIGURE 3 (a) Grand average ERPs for the peripheral distractor from the localizer of Experiment 1 (electrodes CPz, Pz, and POz pooled together), separately for UVF and LVF presentations, revealing a clear polarity reversal peaking at 72 ms (C1), followed by a second one (P1) peaking at 120 ms following stimulus onset. On the ERPs, the error bar corresponds to ± 1 standard error of the mean (SEM); (b) head maps showing the electrodes used (outlined in red) for the analysis of the C1 (CPz, Pz, and POz) and the P1 (O1, O2, and Oz); (c) for the C1 (mean interval: 63–82 ms), the corresponding horizontal topographical voltage maps are shown. Likewise, for the P1 (mean interval: 111–131 ms), the corresponding topographical voltage maps are shown.

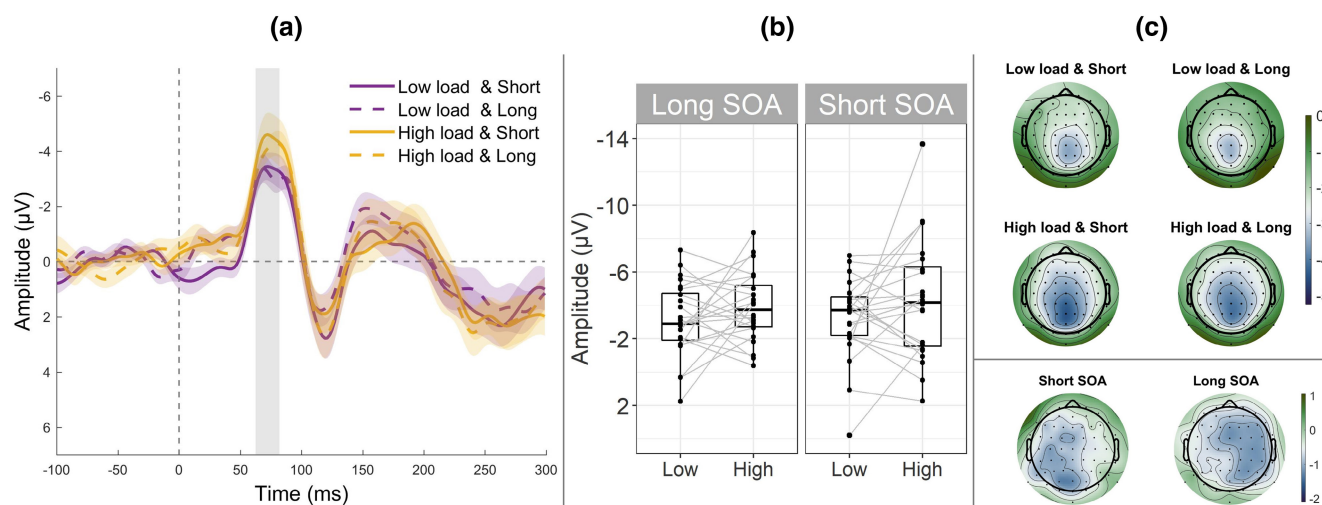


FIGURE 4 (a) Grand average ERPs for the peripheral distractor from Experiment 1, after subtracting dummies (electrodes CPz, Pz, and POz pooled together). On the ERPs, the error bar corresponds to ± 1 standard error of the mean (SEM); (b) the boxplots depict the mean C1 amplitudes during the 63–82 ms interval following stimulus onset after subtracting dummies. Each point in these boxplots represents an individual subject result, with the connecting lines showing the effect of attentional load for each SOA separately; (c) the corresponding topographical voltage map for the C1 (mean interval: 63–82 ms) in each condition is shown at the top. The two topographical maps at the bottom show the relevant C1 ERP-effects (high load minus low load ERP difference) for each SOA separately.

(Figure 2b), the ANOVA showed a significant main effect of Load ($F_{1,23} = 16.857$, $p < .001$, partial $\eta^2 = 0.423$), with fewer errors made in the low than high load condition. The main effect of SOA ($F_{1,23} = 3.527$, $p = .073$, partial $\eta^2 = 0.133$) was marginally significant, showing slightly more false alarms in long than short SOA condition. The interaction between the two factors ($F_{1,23} = 0.254$, $p = .619$, partial $\eta^2 = 0.011$) was not significant. Regarding RTs

(Figure 2c), the ANOVA showed a significant main effect of Load ($F_{1,23} = 6.835$, $p = .015$, partial $\eta^2 = 0.229$), showing faster RTs in the low than high load condition. The effect of SOA ($F_{1,23} = 50.793$, $p < .001$, partial $\eta^2 = 0.688$) was also significant, showing slower RTs in the long compared to the short SOA condition. The interaction between the two factors ($F_{1,23} = 2.110$, $p = .160$, partial $\eta^2 = 0.084$) was not significant.

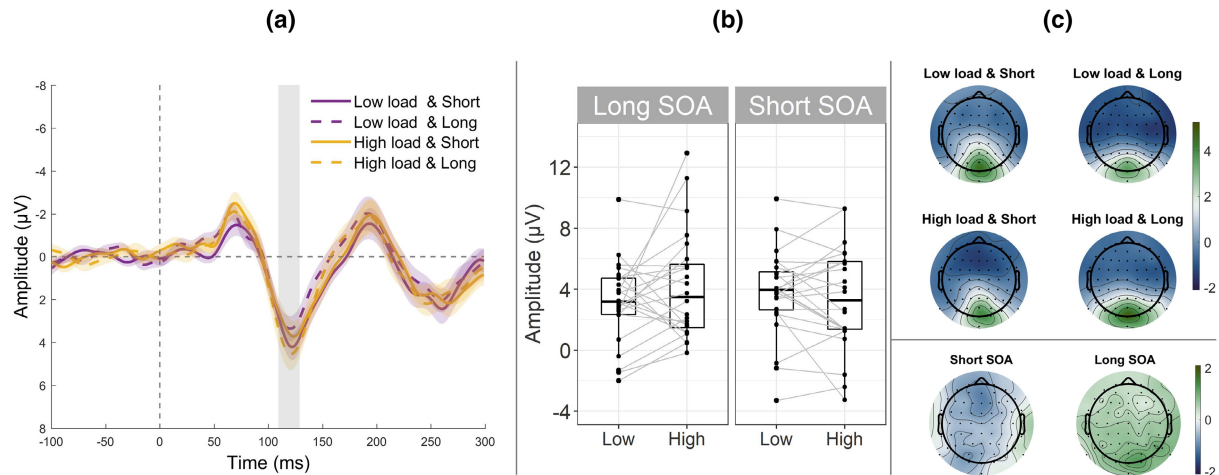


FIGURE 5 (a) Grand average ERPs for the peripheral distractor from Experiment 1 (electrodes O1, Oz, and O2 pooled together). On the ERPs, the error bar corresponds to ± 1 standard error of the mean (SEM); (b) the boxplots depict the mean P1 amplitudes (interval: 111–131 ms). Each point in these boxplots represents an individual subject result, with the connecting lines showing the effect of attentional load for each SOA separately; (c) the corresponding topographical voltage map of the P1 in each condition is shown at the top. The two topographical maps at the bottom show the relevant P1 ERP effects (high load minus low load ERP difference) for each SOA separately.

2.2.2 | Awareness of SOA manipulation of experiment 1

Results showed that 16 of 24 participants (66.67%) were aware of it based on the first question. Moreover, 16 participants (66.67%) found it easier to ignore the peripheral distractor in the short SOA condition, while eight participants (33.33%) reported it was easier in the long SOA condition. For the third question, the results showed that the mean score was 2.58 ($SD=0.72$), suggesting that their confidence was limited.

2.2.3 | C1 and P1 from the localizer of experiment 1

Figure 3 shows a clear-cut C1 ERP component elicited by the peripheral distractor, with its polarity that swapped depending on the position of the stimulus in the visual field (positive for LVF stimulation and negative for UVF stimulation). The C1 (peak latency: 72 ms for UVF presentations) was followed by a P1 component (peak latency: 120 ms for UVF presentations), whose topography indicated a polarity reversal in the opposite direction compared to the C1 (Figure 3b) and it also showed a more occipital scalp distribution.

2.2.4 | C1 from the main session (after removing the dummies) of experiment 1

The ANOVA (Figure 4) showed a statistically significant main effect of Load ($F_{1,23}=6.172$, $p=.021$, partial

$\eta^2=0.212$), indicating a larger C1 in the high load compared to the low load condition. The effect of SOA ($F_{1,23}=0.381$, $p=.543$, partial $\eta^2=0.016$) was not significant, nor the interaction between these two factors ($F_{1,23}=0.054$, $p=.818$, partial $\eta^2=0.002$). The Bayesian ANOVA provided anecdotal evidence for including the main effect of Load ($BF_{\text{incl}}=1.105$). Moderate evidence against including the main effect of SOA ($BF_{\text{incl}}=0.291$) and against including the interaction ($BF_{\text{incl}}=0.280$) was given. Similar results were found when using the uncorrected C1 amplitudes or an individualized peak measurement for this component (see Supporting Information). The Bayesian ANOVAs, however, only provided anecdotal evidence for either including (uncorrected C1) or excluding (individualized C1) the factor Load.

2.2.5 | P1 from the main session of experiment 1

For the P1 (Figure 5), the ANOVA showed that the main effects of Load ($F_{1,23}=0.500$, $p=.487$, partial $\eta^2=0.021$) and SOA ($F_{1,23}=0.054$, $p=.818$, partial $\eta^2=0.002$) were not significant. The interaction between these two factors was marginally significant ($F_{1,23}=3.572$, $p=.071$, partial $\eta^2=0.134$). The Bayesian ANOVA provided moderate evidence against including the main effect of Load ($BF_{\text{incl}}=0.329$) and the main effect of SOA ($BF_{\text{incl}}=0.276$). It provided anecdotal evidence for including the interaction ($BF_{\text{incl}}=1.887$). However, post hoc paired t -tests showed that for both the long SOA ($t_{23}=-1.500$, $p=.147$, Cohen's $d=-0.306$) and short

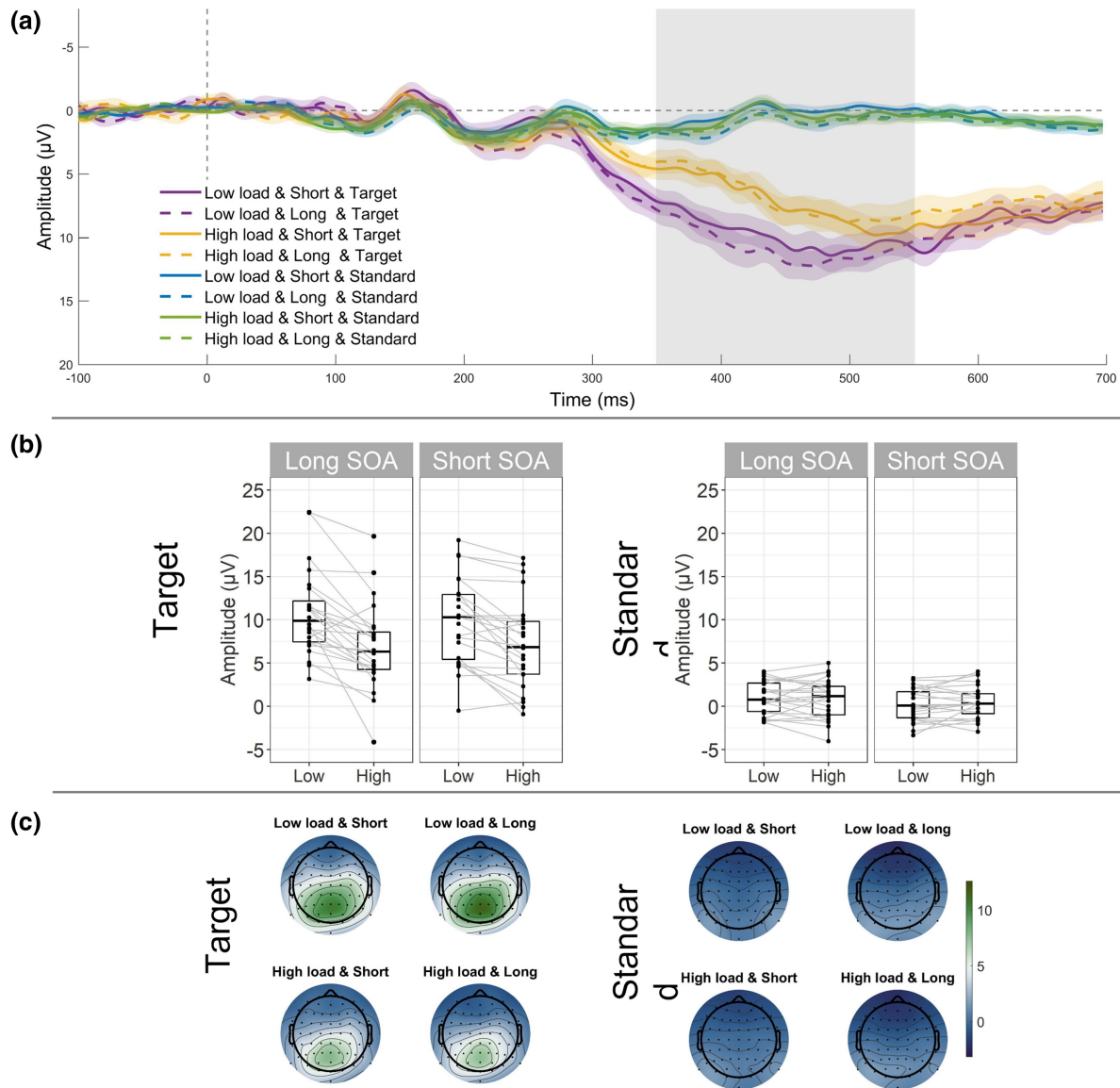


FIGURE 6 (a) Grand average ERPs for the central stimulus from Experiment 1 (electrodes CPz, Pz, and POz pooled together), separately for each condition. On the ERPs, the error bar corresponds to ± 1 standard error of the mean (SEM); (b) the boxplots depict the mean P300 amplitudes (interval: 350–550 ms) for the target and standard central stimulus. Each point in these boxplots represents an individual subject result, with the connecting lines showing the effect of attentional load for each SOA separately; (c) the corresponding topographical voltage map of the P300 for the target and standard central stimulus in each condition is shown.

SOA ($t_{23} = 0.946$, $p = .354$, Cohen's $d = 0.193$), there was a nonsignificant difference between the low and high load condition.

2.2.6 | P300 from the main session of experiment 1

For the P300 (Figure 6), the ANOVA revealed significant main effects of Targetness ($F_{1,23} = 98.498$, $p < .001$, partial $\eta^2 = 0.811$), Load ($F_{1,23} = 23.736$, $p < .001$, partial $\eta^2 = 0.508$) and SOA ($F_{1,23} = 6.401$, $p = .019$, partial $\eta^2 = 0.218$). Moreover, a significant interaction between Targetness

and Load ($F_{1,23} = 32.444$, $p < .001$, partial $\eta^2 = 0.585$) was found. The Bayesian ANOVA provided extremely strong evidence for including the main effect of Targetness ($BF_{\text{incl}} = 1.041 \times 10^{+7}$) and the main effect of Load ($BF_{\text{incl}} = 674.489$) and the interaction between Targetness and Load ($BF_{\text{incl}} = 17,442.383$). Anecdotal evidence was provided against including SOA ($BF_{\text{incl}} = 0.690$). Post hoc t -tests showed that for both low ($t_{23} = 11.272$, $p < .001$) and high load conditions ($t_{23} = 7.389$, $p < .001$), the P300 amplitude was larger for the target than the standard central stimulus. However, this Targetness effect was significantly larger for the low than the high load condition ($t_{23} = 5.696$, $p < .001$, Cohen's $d = 1.163$).

2.3 | Discussion

In Experiment 1, we systematically manipulated the SOA (either short or long) between the central stimulus and the peripheral distractor to assess if the modulation of the C1 by attentional load could depend on this factor and mostly be found for the short SOA. At the behavioral and P3 levels, the effects of load were clearly visible and they translated the use of a different attention control state in the low versus high load condition. Specifically, increasing attentional load at fixation led to a lower hit rate, more false alarms, and longer RTs. The P300 results were also in line with this interpretation. It was larger for targets than standards, with this targetness effect being larger in the low than the high load condition. These results provided strong evidence for the successful manipulation of attentional load. Interestingly, the behavioral results also showed that participants made more errors and responded slower on average in the long compared to the short SOA condition, indirectly suggesting that the peripheral distractor likely had a stronger distraction effect in the long compared to the short SOA condition. Their subjective ratings (cf. awareness of SOA manipulation) also partly confirmed this interpretation.

The results showed that the C1 was actually larger in the high compared to the low load condition, irrespective of the SOA's length. Moreover, it was found regardless of whether the dummies were removed or not, or if an individualized peak measurement of the C1 was used instead (see [Supporting Information](#)). This result is puzzling and opposite to what we had hypothesized a priori for attentional load. We had predicted a lower C1 in the high compared to the low load condition, especially at the short compared to the long SOA. Regarding the subsequent extrastriate P1 component elicited by the peripheral distractor, neither load nor SOA influenced it.

As such, these results for the C1 are not compatible with the load theory of attention according to which the filtering of distractors is stronger in the high compared to the low load condition (Lavie, 1995; Lavie & Tsai, 1994). However, it is noteworthy that this result might be interpreted tentatively and in a post hoc fashion using a working memory load account, as opposed to an attentional load one. As suggested by Lavie (2005) (see also Konstantinou et al., 2014), perceptual load and working memory load can show opposite effects on visual processing and distractibility, with high working memory load actually increasing distractor interference, while perceptual load does the opposite (Dalton et al., 2009; De Fockert et al., 2001; Lavie et al., 2004). More specifically, Lavie and colleagues proposed that loading working memory could be detrimental to attention and impinge on cognitive control. In this situation, the suppression of distractors

could be jeopardized, eventually leading to an increased vulnerability to interference (Allen & Ueno, 2018; De Fockert et al., 2001; Lavie & De Fockert, 2005). Using this framework, we can probably reassess the elected *attentional* load manipulation in Experiment 1, and consider the likely contribution of a working memory load component to the C1 results. Working memory was probably involved because participants were instructed at the beginning of each block to perceive and later remember (to guide their decisions during the block) the angular difference between the target and the standard line orientation. During each block, participants therefore had to process every central stimulus shown and compare it to a template stored in working memory (Olivers et al., 2011), allowing them to tell the difference between target and standard stimuli apart. Reliance on working memory necessarily took place to some extent as the standard and target line orientations were never shown on screen concurrently, but instead, a single titled line bar was shown on every trial above fixation, and it could be either a standard stimulus or a target. Importantly, this working memory-based template matching was likely easier to perform in the low than high load condition. As a result, more interference likely occurred from the peripheral distractor in the high compared to the low load condition and this might be the reason for a larger C1 in the former compared to the latter condition. Hence, we could speculate that task demands included a working memory load component, which imposed a specific attention control state that was different from *attentional* load per se, and this working memory load component eventually influenced early visual processing of the peripheral distractor in V1 as reflected by the C1 in an opposite way compared to attentional load.

Alternatively, the larger C1 found in the high compared to low load condition might be explained by motivation and/or arousal (see also Fu et al., 2009). When task difficulty increased in the high attentional load condition, motivation and/or effort investment likely increased as well (Brehm & Self, 1989; Norman & Bobrow, 1975). Accordingly it is possible that participants put more effort to solve the oddball detection task when it was difficult. Given that motivation can also influence the C1 (Bayer et al., 2017; Rossi et al., 2017), we could imagine that the larger C1 found in the high compared to the low load condition might be explained by a change in motivation between these two conditions. Regarding arousal, it is a state of physiological reactivity (Eysenck, 1982; Robbins & Everitt, 1995), which is related to task difficulty and can contribute to learning and task performance (Causse et al., 2017; Darzi & Novak, 2021; Malmberg et al., 2022; Pecchinenda, 1996). Presumably, in the high load condition, arousal increased compared to the low load condition, which in turn

enhanced the C1 component to the peripheral distractor. However, this explanation appears unlikely because previous studies showed that arousal did not directly act on V1 as selective attention did. Effects of arousal on V1, when observed, likely reflect complex and indirect interactions between multiple neuromodulatory systems, and they can be dissociated from those related to top-down attention (Foucher et al., 2004; Vinck et al., 2015). Moreover, Portas et al. (1998) found that in the absence of attention, arousal did not influence visual cortex activity. Likewise, Proverbio et al. (2021) recently showed that arousal did not modulate the C1 whereas attention did.

We devised Experiment 2 to further explore the possibility that working memory could be involved in this task and influence the C1 to the peripheral distractor in an opposite direction compared to attentional load. To this aim, we used a refined experimental design in Experiment 2 where attentional load was manipulated on a trial-by-trial basis, as opposed to blockwise in Experiment 1. As already mentioned in the introduction, block designs offer a higher signal-to-noise ratio than event-related ones, but the drawback is a drop in sustained attention, with, as a result, the likely presence of unwanted fatigue or habituation effects (for task performance and/or the EEG correlates of target processing and distractor suppression), including mind wandering and/or vigilance decrement. Accordingly, in Experiment 2, we manipulated task difficulty (either easy/low load or difficult/high load) at the single trial level, using a specific cue. At the start of each trial, either the written word *Easy* (for low load) or *Hard* (for high load) was shown and meant to prepare or adjust for the upcoming central stimulus. In every block, a random presentation of these two different cues was achieved such as to reset at the beginning of each trial levels of attentional control and foster rapid and dynamic changes between the low and high load condition across trials. Moreover, the added value of this cueing technique is that a specific ERP component, namely the CNV (Leynes et al., 1998; Mento, 2013; Tecce, 1972) could be recorded and analyzed. The CNV is cue-locked and informs about the actual attentional state of the participants while the peripheral distractor, when shown prior to the central stimulus, is processed. In addition, in Experiment 2, we made the peripheral distractor more unpredictable than in Experiment 1 and showed it either before or after the central stimulus using a short SOA each time. We reasoned that if participants were differentially prepared and set their control level accordingly depending on the cue, showing the peripheral distractor prior to the central stimulus could already reveal a clear attentional load effect on the C1.

3 | EXPERIMENT 2

3.1 | Materials and methods

3.1.1 | Participants

Thirty-seven healthy young adults participated in this experiment. They were recruited using SONA, which is an online system maintained by Ghent University. All participants gave written informed consent and reported no neurological or psychiatric diseases or treatments. The study was approved by the local ethics committee (Faculty of Psychology and Educational Sciences, Ghent University). Four subjects were removed due to poor behavioral performance (i.e., three subjects made too many false alarms: $M=48.96\%$, 52.60% , and 50.52% ; another one had a high false alarms rate in the high load condition: $M=61.46\%$). Two additional subjects were excluded because of excessive eye movements or blinking. For them, when the distractor was presented after the central stimulus, 82.29% and 75% of the epochs had to be rejected, respectively. Therefore, the final sample included 31 subjects (aged 18–29, mean age = 22.42 years, $SD=3.55$ years, eight males).

3.1.2 | Apparatus

The apparatus was identical to that of Experiment 1 except that the resolution of the monitor was changed to 1024×768 pixels.

3.1.3 | Stimuli and task

A 2×2 within-subject design was used, with attentional Load (low vs. high) and distractor Position (pre- vs. post-central-stimulus) as factors. Both factors were manipulated at the single trial level and in each block, a random presentation of these four conditions was achieved. The visual stimuli (standard stimulus, target, and peripheral distractor) in the low load and the high load conditions were identical to those used in Experiment 1. However, several changes were made compared to it:

1. For the main session, each trial lasted longer. It started with a fixation display (blank interval) shown for 1300ms during which participants were encouraged to blink if needed. Then, either the written word *Easy* or *Hard*, indicating the corresponding attentional load level of the upcoming central stimulus (either low or high), was presented 0.3 degrees above the central dot for 200ms, followed by a 1000ms blank interval. Specifically, when *Easy* was presented, participants

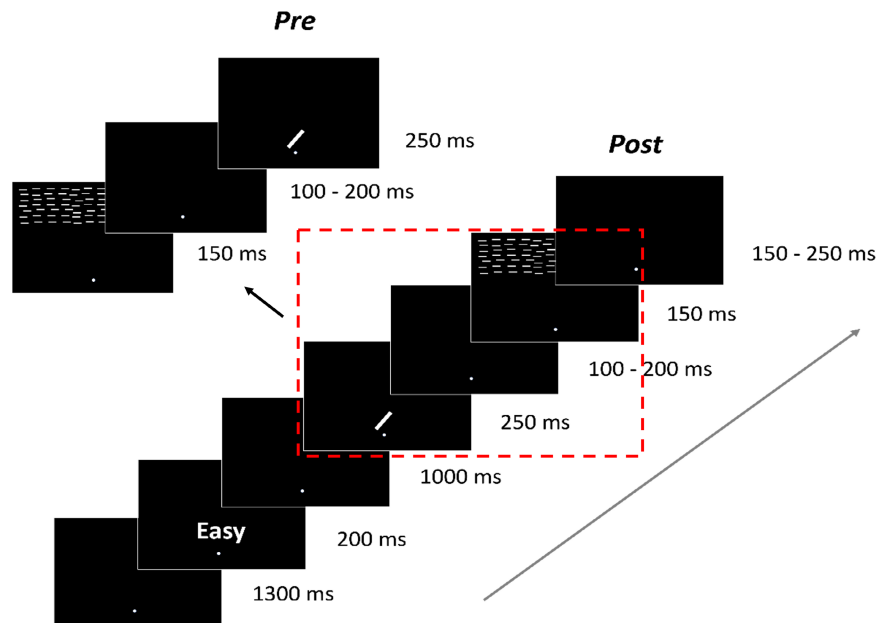


FIGURE 7 Trial structure. At the beginning of each trial, a fixation display (blank interval) was presented for 1300 ms. Then, a visual cue (either the written word *Easy* or *Hard*) was presented above the fixation dot for 200 ms. *Easy* corresponded to low load while *Hard* corresponded to high load. In the post-central stimulus condition, after a blank interval of 1000 ms, the central stimulus (either the standard or the target) was presented for 250 ms. Participants were required to detect targets by pressing the space bar. After a short interval lasting for 100–200 ms, the distractor could be shown in the UVF for 150 ms. In comparison, in the pre-central stimulus condition, the trial structure was the same except that the distractor was shown prior to the central stimulus. In this condition, the distractor was also shown for 150 ms and followed by an interval of 100–200 ms, before the central stimulus was shown for 250 ms. The trial ended with a fixation display shown for 150–250 ms. The red rectangle (dashed line) indicates the main difference between the pre- and post-central stimulus condition.

could anticipate that a large angular difference (i.e., 12 degrees) was used between the target and the standard. When *Hard* was presented, this difference was smaller and amounted to 7 degrees. After the 1000 ms interval, either the central stimulus was shown for 250 ms or the peripheral distractor could appear and stay on screen for 150 ms. If the peripheral distractor appeared first (before the central stimulus; half of the trials), then a short jitter of 100–200 ms was used, afterward the central stimulus was presented for 250 ms. If the central stimulus appeared first after the cue, then it was presented for 250 ms, followed by a jittered interval of 100–200 ms, and then the peripheral distractor was shown for 150 ms. The trial ended with a fixation display shown for 150–250 ms. [Figure 7](#) shows the trial structure in the low load condition.

- The localizer run was simplified to reduce the total duration of the experiment and avoid possible fatigue effects. No specific task was asked, and participants were only required to passively watch the screen throughout each block while keeping fixation. Each trial started with a long interval (fixation display) of 1300 ms, after which the peripheral distractor was presented randomly either in the UVF or LVF for 150 ms. The trial

ended with a 150–250 ms fixation display. It has been shown in previous ERP studies (Rossi & Pourtois, 2012, 2014) that this localizer run carried under passive viewing conditions could elicit a reliable C1 component in response to the peripheral distractor. In analogy with Experiment 1, it was used to analyze and score the C1 using independent EEG data.

3.1.4 | Procedure

The experiment consisted of three successive phases: practice, main session, and localizer. First, participants completed a practice block with 30 trials before the main session started, consisting of four blocks with 90 trials each; 45 per load level. For each of them, eight targets and 37 standards were presented, in a pseudo-random order. These 45 trials were further divided into two conditions (pre- vs. post-central-stimulus). In the pre-condition, 15 distractors and eight dummies were shown, while in the post-condition, 15 distractors and seven dummies were presented. After finishing the main session, participants were asked to perform an additional localizer block consisting of 100 trials, with 50 distractors shown in the UVF and 50 in the LVF.

TABLE 2 Average number of epochs included in the averaging after preprocessing, for each stimulus type separately.

	Peripheral distractor	Target	Standard stimulus	Cue
Low load & Pre	41.29 (5.19)	10.48 (1.34)	41.42 (2.36)	160.58 (5.22)
Low load & Post	31.65 (10.31)	11.19 (0.83)	43.45 (1.98)	
High load & Pre	40.90 (5.31)	11.10 (1.11)	42.48 (2.22)	161.52 (5.29)
High load & Post	31.03 (9.87)	10.90 (1.07)	44.19 (1.78)	

Note: Before preprocessing, 48 trials were retrieved for the distractor for each condition; for the target (and when a peripheral distractor could also be presented), 12 trials were retrieved for each condition; for the standard stimulus (when no distractor was presented), 48 trials were retrieved for each condition. For the cue, 180 trials were retrieved for each condition (i.e., low vs. high load). Standard deviation is shown in parentheses.

3.1.5 | Statistical analyses

Data processing and statistical analyses were identical to Experiment 1, except for the epoching. For the central stimulus, we used a $-110/+600$ ms around the stimulus onset as segmentation. For the peripheral distractor (or dummy), we first used a $-700/+300$ ms time window around the stimulus onset. After excluding the epochs contaminated by motor activity related to target processing (for the post-central stimulus condition), we re-epoched them using a $-100/300$ ms interval. For the cue, we used a $-110/+1800$ ms time window around its onset. **Table 2** shows the average number of epochs used for averaging after preprocessing for each condition separately.

In addition, we found that the mean peak latency of the C1 (i.e., 78 ms after stimulus onset) and the P1 (i.e., 127 ms after stimulus onset) for the peripheral distractor recorded during the localizer run differed from those in the main session (i.e., 82 ms for the C1 and 123 ms for the P1). We reckoned that this difference could be attributed to the different stimulus parameters and procedure used in the localizer run during which only peripheral distractors were presented either in the UVF or LVF, in a random order. Accordingly, we determined the time intervals of the C1 (72–92 ms) and the P1 (113–133 ms) based on the EEG data recorded during the main session rather than the localizer (however, see **Supporting Information** for the C1 results when using the localizer data to identify its peak latency). The P300 component was scored as a mean amplitude during the 400–600 ms interval following stimulus onset. The CNV component was scored at electrodes C1, C2, and Cz using a mean amplitude measurement (i.e., 1000–1200 ms following cue onset).

For the C1, P1, and P300, repeated-measures ANOVAs were conducted using their mean amplitudes. When a significant interaction was found, follow-up post hoc *t*-tests were performed. For the CNV, a paired *t*-test was conducted comparing its mean amplitude in the low versus high load condition. Similar to Experiment 1, for all EEG results, complementary Bayesian repeated-measures ANOVAs and Bayesian *t*-tests were also conducted.

Last, we also conducted a topographical ERP mapping analysis on the ERP data for the peripheral distractor (C1) and the visual cue (CNV) using CARTOOL 3.91 (<https://sites.google.com/site/cartoolcommunity/>) to assess if the topography of these two ERP components might change depending on attentional load and distractor position. The dominant topographical maps for the C1 and CNV components were first identified based on the grand average ERP data using a K-means cluster analysis. A cross-validation procedure was used to identify the optimal number of dominant topographies accounting for the variance in these ERP data (Pascual-Marqui et al., 1995). We then fitted the dominant topographical maps back to the individual subject data such as to extract their Global Explained Variance (GEV). These GEV values were eventually submitted to statistical analyses (C1: repeated-measures ANOVA with Load and Position as within-subject factors; CNV: repeated-measures ANOVA with Cue and Map as within-subject factors). The results of these auxiliary topographical analyses on the C1 (where no significant effects emerged) and the CNV (where a highly significant topographical difference was found between the two cues) can be found in **Supporting Information**.

3.2 | Results

3.2.1 | Behavioral results of experiment 2

The ANOVA on hit rates (**Figure 8a**) revealed a significant main effect of Load ($F_{1,30}=18.551, p < .001$, partial $\eta^2=0.382$), showing a higher accuracy in the low than high load condition. The effect of Position ($F_{1,30}=33.086, p < .001$, partial $\eta^2=0.524$) was also significant, with a higher accuracy in the post- compared to the pre-central-stimulus condition. The interaction between the two factors did not reach significance ($F_{1,30}=0.391, p = .537$, partial $\eta^2=0.013$). For false alarms (**Figure 8b**), the ANOVA showed a significant main effect of Load ($F_{1,30}=23.338, p < .001$, partial $\eta^2=0.438$), with fewer errors made in the low than high load condition. The main effect of Position ($F_{1,30}=0.550, p = .464$, partial $\eta^2=0.018$) was not significant, nor the interaction between

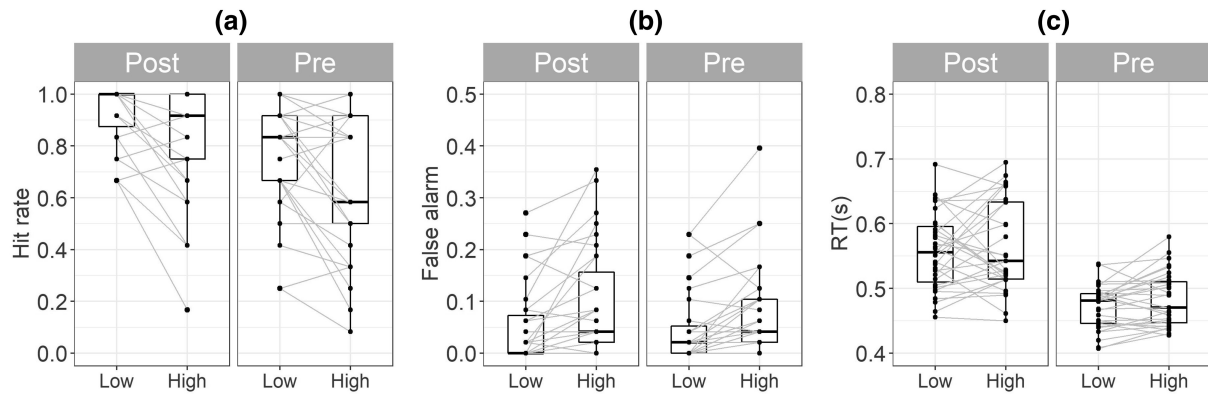


FIGURE 8 The boxplots depict the behavioral results of Experiment 2 for each condition separately. (a) hit rate; (b) false alarm rate; (c) mean RTs for correct responses. Each point in these boxplots represents an individual subject result, with the connecting lines showing the effect of attentional load for each position separately.

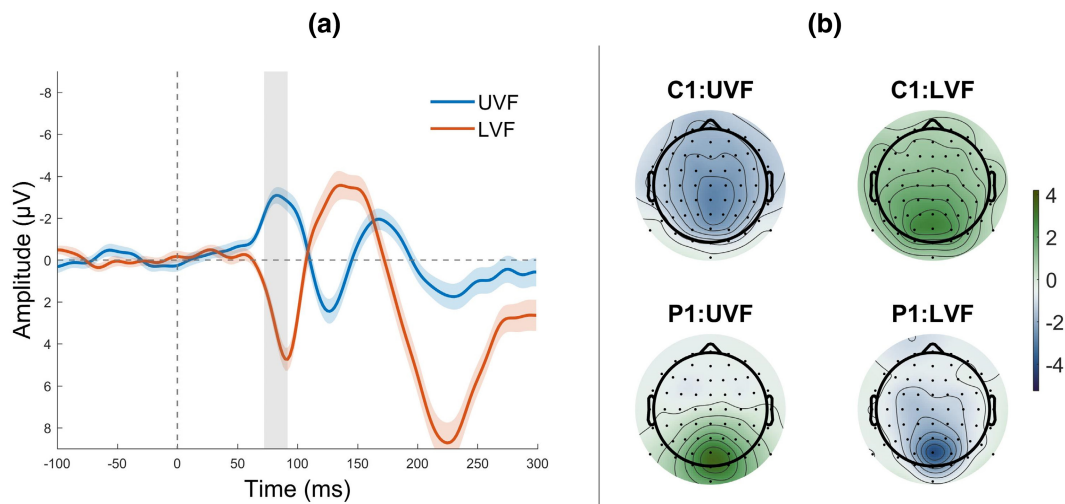


FIGURE 9 (a) Grand average ERPs for the peripheral distractor from the localizer of Experiment 2 (electrodes CPz, Pz, and POz pooled together), separately for the UVF and LVF, revealing a clear polarity reversal peaking at 78 ms (C1), followed by a second one (P1) peaking at 127 ms following stimulus onset. On the ERPs, the error bar corresponds to ± 1 standard error of the mean (SEM); (b) for the C1 (mean interval: 68–88 ms), the corresponding horizontal topographical voltage maps are shown. Likewise, for the P1 (mean interval: 117–137 ms), the corresponding topographical voltage maps are shown.

the two factors ($F_{1,30}=0.373$, $p=.546$, partial $\eta^2=0.012$). For RTs (Figure 8c), the ANOVA showed a significant main effect of Position ($F_{1,30}=202.045$, $p<.001$, partial $\eta^2=0.871$), with faster RTs for the pre- than the post-central stimulus condition. Neither the main effect of Load ($F_{1,30}=1.476$, $p=.234$, partial $\eta^2=0.047$) nor the interaction between the two factors ($F_{1,30}=0.342$, $p=.563$, partial $\eta^2=0.011$) was significant.

3.2.2 | C1 and P1 from the localizer of experiment 2

Figure 9a shows clear-cut C1 and P1 ERP components elicited by the peripheral distractor with their polarities

that were reversed depending on the position of the stimulus in the visual field. The C1 (peak latency: 78 ms for UVF presentation) was followed by a P1 component (peak latency: 127 ms for UVF presentation), whose topography was different (Figure 9b), and more occipital compared to the C1 showing an occipito-parietal scalp distribution.

3.2.3 | C1 from the main session of experiment 2

The ANOVA (Figure 10) showed a marginally significant main effect of Position ($F_{1,30}=4.129$, $p=.051$, partial $\eta^2=0.121$), with a trend of higher C1 in the post- than pre-central stimulus condition. The effect of Load

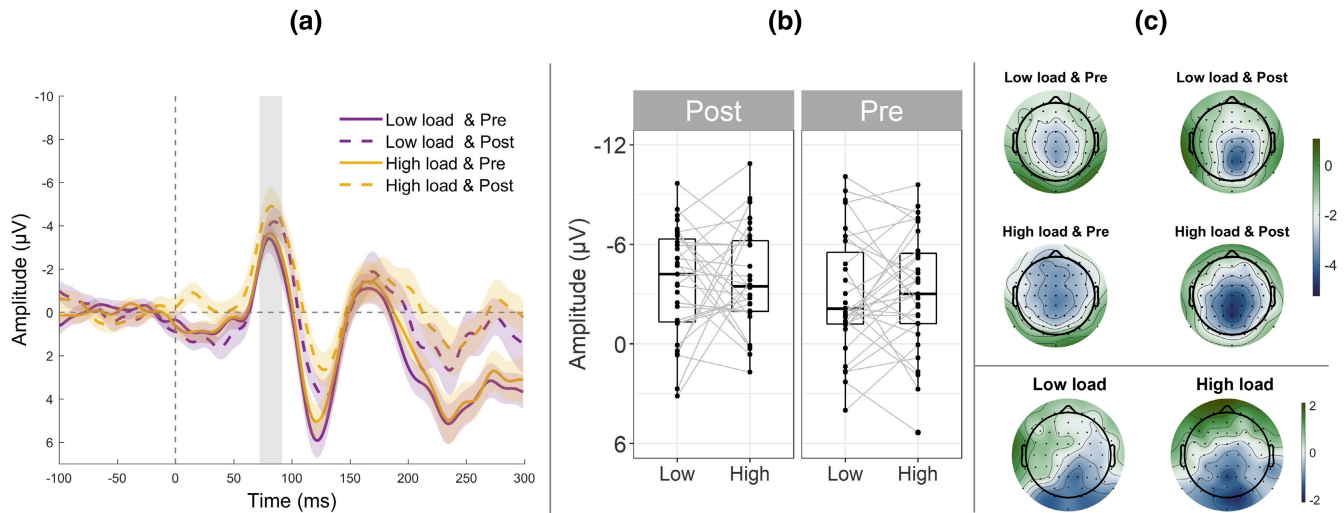


FIGURE 10 (a) Grand average ERPs for the peripheral distractor from Experiment 2, after subtracting dummies (electrodes CPz, Pz, and POz pooled together). On the ERPs, the error bar corresponds to ± 1 standard error of the mean (SEM); (b) the boxplots depict the mean C1 amplitudes during the 72–92 ms post-stimulus interval after subtracting dummies. Each point in this boxplot represents an individual subject result, with the connecting lines showing the effect of attentional load for each position separately; (c) The corresponding topographical voltage map for the C1 in each condition is shown at the top. The two topographical maps at the bottom show the relevant C1 ERP-effects (post minus pre-central stimulus ERP difference) for each load level separately.

($F_{1,30}=0.954$, $p=.337$, partial $\eta^2=0.031$) and interaction between this factor and Position ($F_{1,30}=0.143$, $p=.708$, partial $\eta^2=0.005$) did not reach significance. The Bayesian ANOVA provided anecdotal evidence against including the main effect of Position ($BF_{\text{incl}}=0.905$), and moderate evidence against including the main effect of Load ($BF_{\text{incl}}=0.330$) and the interaction ($BF_{\text{incl}}=0.308$). In the three additional analyses (uncorrected C1, an individualized peak measurement of the C1, and C1 using the latency based on the localizer), the effect of Position was not significant (see [Supporting Information](#)). However, the topographical analysis also showed a marginally significant difference between the pre- and post-central stimulus condition (see [Supporting Information](#)).

3.2.4 | P1 from the main session of experiment 2

For the P1 ([Figure 11](#)), the ANOVA showed a significant main effect of Position ($F_{1,30}=183.363$, $p<.001$, partial $\eta^2=0.554$), with a higher P1 in the pre- than post-central stimulus condition. Neither the main effect of Load ($F_{1,30}=0.147$, $p=.704$, partial $\eta^2=0.005$) nor the interaction between these two factors ($F_{1,30}=0.615$, $p=.439$, partial $\eta^2=0.020$) was significant. The Bayesian ANOVA provided extreme evidence for including the main effect of Position ($BF_{\text{incl}}=18,339.564$), moderate evidence

against including the main effect of Load ($BF_{\text{incl}}=0.253$), and anecdotal evidence against including the interaction ($BF_{\text{incl}}=0.338$).

3.2.5 | P300 from the main session of experiment 2

For the P300 ([Figure 12](#)), the ANOVA showed significant main effects of Targetness ($F_{1,30}=91.618$, $p<.001$, partial $\eta^2=0.753$) and Load ($F_{1,30}=13.817$, $p<.001$, partial $\eta^2=0.315$). Position was not significant ($F_{1,30}=2.766$, $p=.107$, partial $\eta^2=0.084$). Moreover, a significant interaction between Targetness and Load was found ($F_{1,30}=7.434$, $p=.011$, partial $\eta^2=0.199$). The Bayesian ANOVA indicated extreme evidence for including the main effect of Targetness ($BF_{\text{incl}}=8.806 \times 10^{+7}$), strong evidence for including the main effect of Load ($BF_{\text{incl}}=28.395$), anecdotal evidence for including the main effect of Position ($BF_{\text{incl}}=1.198$), and moderate evidence for including the interaction between Targetness and Load ($BF_{\text{incl}}=5.639$). Post hoc t -tests showed that for both low ($t_{30}=9.327$, $p<.001$, Cohen's $d=1.675$) and high load conditions ($t_{30}=7.072$, $p<.001$, Cohen's $d=1.270$), the P300 amplitude was larger for the target than the standard stimulus. However, this Targetness effect was significantly larger for the low than high load condition ($t_{30}=2.727$, $p=.011$, Cohen's $d=0.490$).

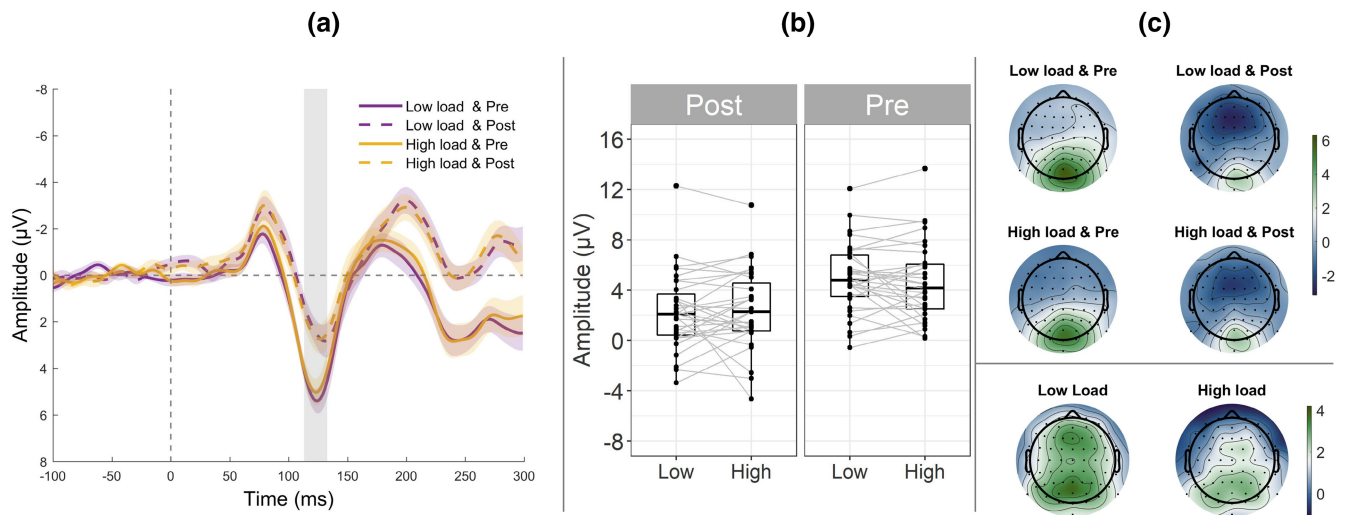


FIGURE 11 (a) Grand average ERPs for the peripheral distractor from Experiment 2 (electrodes O1, Oz, and O2 pooled together). On the ERPs, the error bar corresponds to ± 1 standard error of the mean (SEM); (b) The boxplots depict the mean P1 amplitudes (interval: 117–137 ms). Each point in these boxplots represents an individual subject result, with the connecting lines showing the effect of attentional load for each position separately; (c) the corresponding topographical voltage map for the P1 in each condition is shown at the top. The two topographical maps at the bottom show the relevant P1 ERP-effects (pre-minus post-central stimulus ERP difference) for each load level separately.

3.2.6 | CNV from the main session of experiment 2

As shown in Figure 13, the effect of Load on CNV amplitude was marginally significant, with a trend toward a more negative CNV amplitude in the low compared to the high load condition ($t_{30} = -2.014$, $p = .053$, Cohen's $d = -0.362$). However, a supplementary topographical analysis clearly indicated that a significant difference was found during the CNV time interval between these two conditions, suggesting that different brain regions were involved for the easy (low load) versus difficult cue (high load) during it (Michel & Murray, 2012; see Supporting Information).

3.3 | Discussion

In Experiment 2, we used a trial-by-trial manipulation of task difficulty to assess if the C1 ERP component elicited by the peripheral distractor could be modulated by attentional load. This was achieved by a cueing technique, informing participants at the beginning of each trial whether the upcoming target detection was either easy (low load) or hard (high load). Moreover, the peripheral distractor was presented either shortly before or after the central stimulus, to increase uncertainty and to foster its suppression by the activation of top-down attention control mechanisms.

Behavioral and P300 results were similar to those of Experiment 1 and clearly showed that attentional load

had a substantial influence on the visual processing of the central stimulus. Specifically, compared to the low load condition, participants missed more targets, made more false alarms,¹ and were slower in the high load condition. Moreover, the P300 was larger for targets than standards, and this targetness effect was reduced in the high compared to the low load condition. These results are entirely consistent with those reported in Experiment 1, but also with earlier ERP studies published in the literature on attentional load (Rauss et al., 2009, 2012; Rossi & Pourtois, 2012, 2014). However, unlike these previous studies that employed a block design and reported a modulation of the C1 as a function of attentional load, Experiment 2 did not show any such modulation, even though a trial-by-trial manipulation of task difficulty was used and the peripheral distractor could be shown either before or after the central stimulus. Accordingly, with respect to attentional load, the use of an event-related design does not appear to yield different and clearer effects on the C1 than a block design (see Experiment 1).

In addition, the results of Experiment 2 also suggest that the C1 could be modulated by the position of the peripheral distractor (regardless of attentional load), which was larger for the post- than the pre-central stimulus condition. Moreover, this position effect on the C1, which was marginally significant only, could not be explained easily

¹This change in the false alarm rate might indicate a change in the processing strategy adopted by the participants in the high compared to the low load condition.

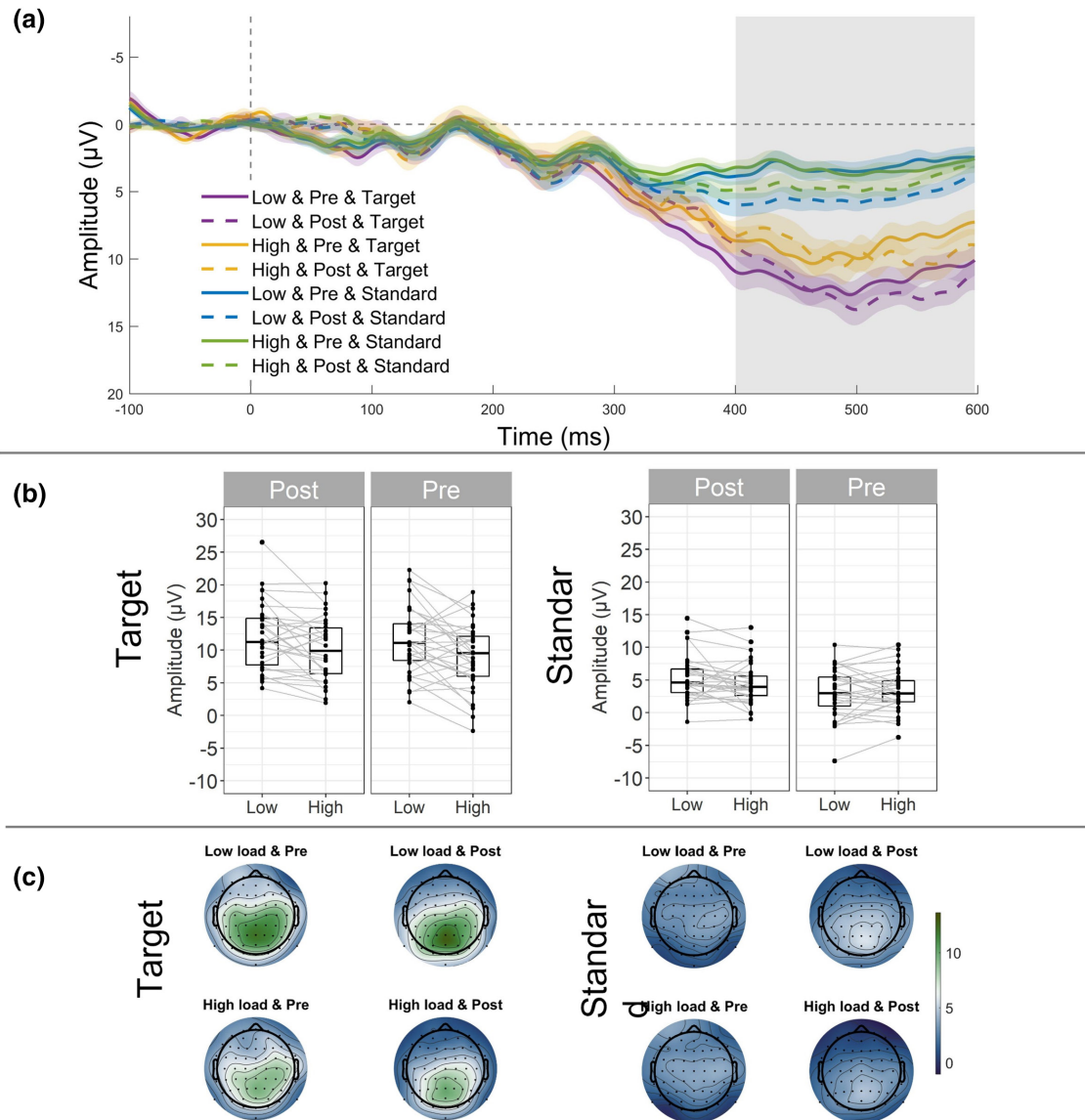


FIGURE 12 (a) Grand average ERPs for the central stimulus from Experiment 2 (electrodes CPz, Pz, and POz pooled together), separately for each condition. On the ERPs, the error bar corresponds to ± 1 standard error of the mean (SEM); (b) the boxplots depict the mean P300 amplitudes (interval: 400–600 ms) for the target and standard stimulus, separately. Each point in these boxplots represents an individual subject result, with the connecting lines showing the effect of attentional load for each position separately; (c) the corresponding topographical voltage map of the P300 for the target and standard central stimulus in each condition is shown.

by overlapping ERP activities (from the preceding stimulus, either cue or central stimulus) as we subtracted the ERPs of the dummies from it. This larger C1 for the post- than pre-central stimulus condition was compensated by a significantly lower extrastriate P1 component for the former compared to the latter condition (see Figure 11), thereby confirming that the processing of the peripheral distractor was qualitatively different during the pre- versus post-central-stimulus interval, and importantly, an early *attention* or perhaps (*error-*) *prediction* effect in V1 at the C1 level could be found (Den Ouden et al., 2012; Kok et al., 2011). We return to this interpretation in the General Discussion here below.

Another important result of Experiment 2 pertains to the CNV component time-locked to the cue. Based on the results of Experiment 1 and independent evidence, we had expected it to be larger in the high compared to the low load condition, as this would reflect enhanced preparation in the former compared to the latter condition (De Loof et al., 2019). However, here we found a marginally significant effect in the opposite direction: a more negative (and hence larger) CNV in the low than high load condition. Although this effect was marginally significant only when using a standard amplitude measurement performed at a few electrodes, the supplementary topographical analysis clearly showed that the CNV had a significantly different

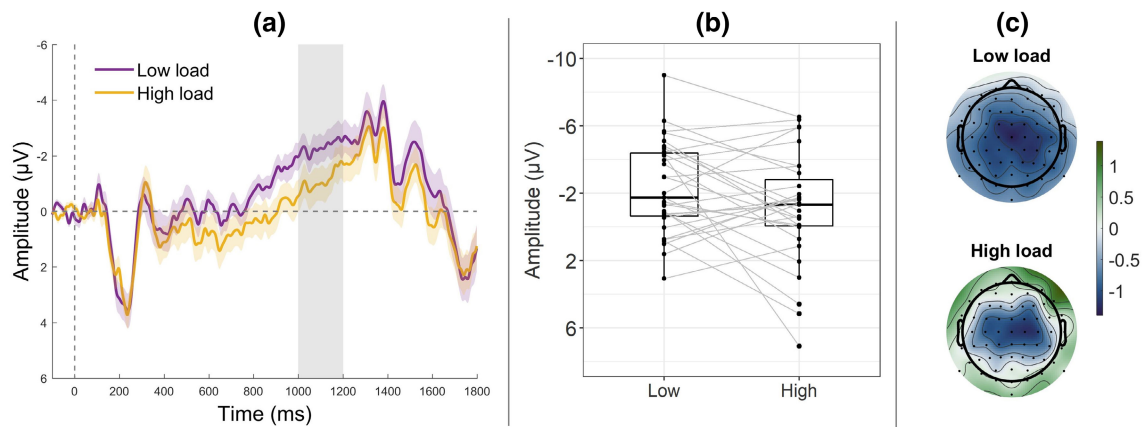


FIGURE 13 (a) Grand average ERPs for the cue from Experiment 2 (electrodes C1, C2, and Cz pooled together), separately for each of the two conditions (low vs. high load). On the ERPs, the error bar corresponds to ± 1 standard error of the mean (SEM); (b) The boxplots depict the mean CNV amplitude (interval: 1000–1200 ms after cue onset). Each point in the boxplot represents an individual subject result, with the connecting lines showing the effect of attentional load; (c) the corresponding topographical voltage map of the CNV is shown for each condition separately.

scalp distribution (and hence underlying neural generators) in the low compared to the high load condition. As such, this result is not merely compatible with a gain in attention control or preparation upon the encounter of the *hard* cue compared to the *easy* one (De Loof et al., 2019; Schevernels et al., 2014; Vanlessen et al., 2012). However, and as previously surmised based on the (C1) results of Experiment 1 (see Discussion), this result for the CNV could tentatively be explained by the contribution of a working memory load component that eventually blurred and even swapped this load-related CNV effect. More specifically, in the low load condition, participants could easily use the template stored in working memory and used to tell the angular difference between the standard and target stimulus apart. In this condition, the cue therefore helped them to retrieve and activate *proactively* this template, eventually leading to a clear CNV component. However, in the high load condition, this template was likely more difficult to retrieve from working memory, and participants relied more in this condition on reactive cognitive control: They did not prepare proactively, but mostly *waited* for the central stimulus to decide whether it was a target or not. As a result, the CNV was smaller in this condition than in the low load condition. Importantly, whether working memory (besides attention) is involved or not remains to be shown with additional data and results, but these ERP results for the cue (CNV) clearly confirm that a different preparation or anticipatory state was elicited by the *easy* versus *hard* visual cue.

4 | GENERAL DISCUSSION

In the current study comprising two different EEG experiments, we used a visual oddball task similar to that of

previous studies (Rauss et al., 2009; Rossi & Pourtois, 2012, 2014, 2017) but introduced specific methodological changes and improvements compared to it, with the aim to increase the likelihood to observe a significant modulatory effect of attentional load on the initial stage of visual processing following stimulus onset in V1 captured by the C1 ERP component. In Experiment 1, we manipulated both task difficulty and the SOA (either short or long) between the central stimulus and the peripheral distractor, using a block-wise design. In Experiment 2, task difficulty was manipulated on a trial-by-trial basis using a specific cueing technique. Moreover, the peripheral distractor was shown either before or after the central stimulus. The results of these two experiments largely converge and allow us to draw several conclusions about the malleability of the C1 to attentional load.

First and foremost, we did not find a modulation of the C1 by attentional load, neither in Experiment 1 where a block design was used nor in Experiment 2 where an event-related design was used instead. Moreover, regardless of the specific experimental design used, the subsequent extrastriate P1 component was not modulated by attentional load either. These ERP results are compatible with some earlier ERP studies (Ding et al., 2014; Herde et al., 2022; Rauss et al., 2009, 2012; Wolf et al., 2022), but not with other ones (Fu et al., 2010b; Rossi & Pourtois, 2012). According to the load theory of selective attention (Lavie, 1995, 2005; Lavie et al., 2004; Lavie & Tsai, 1994), under high load, the filtering or suppression of task-irrelevant distractors is facilitated compared to low load, and this attention effect is deemed *perceptual*, influencing early stages of visual processing. As a result, a reduction of sensory processing of the (peripheral) distractor should be observed for the high compared to the

low load condition, including in V1 (Schwartz et al., 2005). However, the C1 (and P1) results of the two experiments reported in this study do not confirm this assumption. In both experiments, we did not observe a reduction of the C1 in the high compared to the low load condition even though the behavioral and P3 results clearly showed that we successfully induced and could contrast two distinct attentional control states that were compatible with either a low or a high attentional load level used by the participants. In both experiments, accuracy decreased (and RTs increased in Experiment 1) when task difficulty increased, and the P3 amplitude also varied accordingly. Based on these results, we could therefore ascertain that attentional load had a major impact on the central stimulus, whose perceptual processing was definitely enhanced in the low compared to the high load condition. Besides the lack of C1 modulation by attentional load, we also found that the subsequent extrastriate P1 component was not affected by this factor either. This latter result is not surprising as many previous ERP studies on attentional load (Ding et al., 2014; Herde et al., 2022; Rauss et al., 2009, 2012; Wolf et al., 2022) already reported a lack of P1 modulation (but see Fu et al., 2010b for an exception). In comparison, several previous ERP studies already reported P1 modulations as a function of spatial attention (see, e.g., Baumgartner et al., 2018; Di Russo et al., 2003; Martínez et al., 1999). Hence, this extrastriate component appears to be more sensitive to spatial attention than attentional load. However, additional ERP studies where these two classes of attention control effects could directly be compared with each other are needed in order to corroborate this conclusion.

To account for these C1 and P1 results, we could imagine that the peripheral distractor we have used (which was always shown in the UVF during the main session) was actually not compatible with a real distractor stimulus (i.e., it did not compete with the central stimulus), and hence, there was actually little or no need to filter it out since it did not create a strong interference. Although we cannot formally rule out this interpretation, two (behavioral) results reported in this study are not immediately compatible with it, however. First, in Experiment 1, the use of a long SOA caused more errors and longer RTs than a short SOA, indirectly suggesting that it was easier to ignore it in the latter condition (see also awareness ratings results). Second, in Experiment 2, participants were faster (but at the same time also missed more targets) when the peripheral distractor was shown prior to the central stimulus, compared to after it. This result likely suggests that a larger interference effect was created by the peripheral distractor in the former condition. Hence, this peripheral stimulus was perhaps not a real distractor in a strict sense (Lavie, 2005), but it did create however some interference,

therefore implying that (some) attention control was needed for it.

Furthermore, our oddball visual discrimination task was also different from previous ERP studies on attentional load where either simple detection (low load) or conjunction search (high load) based on color and shape was used instead (Rauss et al., 2009, 2012; Schwartz et al., 2005). Here, we used a visual discrimination task based on line orientation, which might artificially have increased peripheral distractor processing throughout since it consisted of a texture made up of discontinuous line segments. Presumably, in these conditions, the early filtering of this peripheral distractor at the C1 (and P1) level in the high load condition could be attenuated because it was somewhat relevant (i.e., sharing a main low-level feature with the central stimulus, namely line orientation).

Interestingly, in Experiment 1, the C1 to the peripheral distractor was actually larger in the high compared to the low load condition, and this result was significant in all the three analyses performed (i.e., C1 computed after subtracting dummies, uncorrected C1 amplitudes, or C1 measured using an individualized mapping procedure). Hence, we found an enhanced V1 activity elicited by the peripheral distractor early on following its onset in the high compared to low load condition. Moreover, this *attention* effect occurred irrespective of the SOA's length, suggesting that it was probably not short lasting or phasic as we would expect it to be for attentional load, however (see also our hypothesis along these lines in Introduction). Notably, previous studies have reported opposite effects on visual perception (and attention) for perceptual load and working memory load (Dalton et al., 2009; De Fockert et al., 2001; Lavie et al., 2004). When working memory load is increased, distractor suppression is not reduced, but the interference effect created by the distractor is actually larger compared to the condition where working memory load is kept low (Allen & Ueno, 2018; De Fockert et al., 2001; Lavie & De Fockert, 2005). Given the larger C1 found for the high than low load condition in Experiment 1, we could therefore assume that a specific working memory component might be involved in our task and eventually account for this unexpected result. In agreement with this interpretation, in both experiments, target detection was likely achieved by means of template matching in working memory (Olivers et al., 2011), and not simply perceptual or attentional load (based on external visual processing exclusively). On each and every trial, participants had to detect a possible deviation between a predefined line orientation (standard) and a tilted one (target), but to perform this visual discrimination task, reliance on working memory was probably needed because a single line bar (either standard or target) was only shown on each and every trial. Hence, they had to match

the incoming stimulus (i.e., this single line bar at fixation) to a representation of it stored in working memory, and eventually decide, based on this template matching, whether it was a target (i.e., the orientation of the central stimulus actually deviated from the standard one) or not. In the high load condition, this working memory-based process was more difficult to perform than in the low load condition, eventually resulting in a weaker filtering of the peripheral distractor at the C1 level compared to the low load condition. In comparison, no such working memory-based template matching was needed in the ERP study performed by Rauss et al. (2009) because a different visual discrimination task was used (see also here above). In the low load condition, participants had to detect a single feature based on the visual stimulus (color), while in the high load condition, a conjunction of features (color plus shape) had to be monitored based on it. Importantly, in both cases, visual processing of the stimulus was required, without activation of and comparison with a representation of it stored in working memory. Interestingly, in this situation, a larger C1 for the low compared to the high load condition was reported, in agreement with a genuine attentional load effect (Lavie, 2005).

Additional support for this working memory account comes from the CNV results of Experiment 2. Given that the CNV reflects specific preparation and attention processes (Frost et al., 1988; Grentt-Jong & Woldorff, 2007; Walter et al., 1964), we a priori had expected it to be larger in the high than low load condition because the former obviously required more preparation and attention than the latter. However, our results showed the exact opposite pattern, with a larger CNV in the low (*Easy* cue) than the high load condition (*Hard* cue). Previous ERP studies already reported an attenuation of the CNV in conditions or for tasks where a high working memory load component was required (Delse et al., 1972; McEvoy et al., 1998; Tecce, 1972; Tecce & Scheff, 1969). In agreement with the working memory account raised here above, we can therefore conjecture that in the high load condition, when participants encountered the *hard* cue, they probably tried to retrieve and remember the angular difference between the standard and target stimulus, and this was probably difficult to do (taxing working memory). In comparison, in the low load condition, it was easier to remember (as well as process) this angular difference, and hence adequately prepare for the upcoming stimulus based on the cue, thereby leading to a larger CNV in this condition. Combined with the C1 results of Experiment 1, the CNV results of Experiment 2 therefore lend support to the assumption that our oddball visual discrimination task was not a pure perceptual task, but working memory was likely involved to solve it as well. Because working memory load can create opposite effects on visual perception

(and attention) than attentional load (see Lavie, 2005), it appears plausible to assume that the lack of systematic C1 modulation by attention load in Experiments 1 and 2 could tentatively be imputed to this factor. We note, however, that in Experiment 2, we did not observe a larger C1 for the high than low load condition. This might result from the specific cue and event-related design used in that experiment, which may have reduced the interference effect created by the peripheral distractor. In comparison, in Experiment 1 where a block design was used, it is conceivable that no such gain or proactive suppression of distractor's interference was promoted (and hence, the C1 was larger in the high than low load condition). However, this interpretation in terms of working memory load is post hoc. Accordingly, it appears important in future (ERP) studies to explore more carefully and systematically the possible contribution of working memory load, besides or in combination with attentional load, to the C1 ERP component and more generally, distractor suppression. In this context, the contralateral delay activity (CDA) might also be used in future studies, as it is considered to be a reliable ERP correlate of visual working memory capacity (Luck et al., 2000; McCollough et al., 2007; Vogel & Machizawa, 2004). This component is usually recorded at posterior-parietal electrodes on the side/hemisphere opposite to where the visual items to be remembered are presented (using a visual array). Previous studies have found that the CDA amplitude was larger when the number of items to be remembered increased, indicating in turn a greater involvement of working memory (Luck & Vogel, 2013; Luria et al., 2016; Luria & Vogel, 2011). Thus, it might be interesting in future studies to harness the CDA (besides the CNV), using a different experimental procedure with lateralized stimulus presentations, to confirm the involvement of a working memory component in this oddball visual discrimination task based on line orientation. A main limitation of the experimental design used in Experiment 2 is that it does not unambiguously allow to directly relate this CNV effect to working memory.

Another worth-discussing finding concerns the amplitude modulation of the C1 and P1 components by distractor position, as shown in Experiment 2. When the peripheral distractor was presented prior to the central stimulus (pre-central), the C1 was smaller compared to the condition where it followed it (post-central). However, here too, caution is needed in the interpretation of this effect as it was only marginally significant (and was not significant when uncorrected C1 amplitudes were used or the C1 was computed using an individualized mapping procedure, see [Supporting Information](#)). However, when considering the entire ERP waveforms (see [Figures 10 and 11](#)), it appears clear that a broader and component unspecific effect driven by position took place, whereby the global ERP activity

(and morphology) in response to the distractor substantially varied between the pre- and post-central stimulus condition. Hence, although the effect of position was marginally significant only for the C1, the P1 was clearly larger in the pre- compared to the post-central stimulus condition, and moreover, the subsequent visual ERPs (e.g., N1) were also substantially reduced in the latter condition. At this point, we believe three different, albeit not necessarily mutually exclusive, explanations could be raised to account for this position effect (influencing the C1 and later ERP components). Before we turn to them, we first would like to emphasize that it appears highly unlikely that this position effect would simply result from the contamination of preceding (and overlapping) ERP components or activities. First, we used a stringent ERP data processing where contamination by the preceding stimulus (especially for peripheral distractor in post-central stimulus condition) was kept minimum because we only used and computed visual ERPs for the peripheral distractor when it followed a standard central stimulus (not a target), for which no response was required. Trials with motor responses were not included for the ERP data analysis of the peripheral distractor. We also used a jittered interval between the central stimulus and peripheral distractor. Moreover, for the main analysis, we also removed from the C1 and P1 to the peripheral distractor the ERP activities of dummies, and this way minimized ERP overlap.

To account for this reduced C1 component in the pre- than post-central stimulus condition, the signal suppression hypothesis could first be invoked (Gaspelin et al., 2017; Luck et al., 2021). According to it, salient distractors can be suppressed by a top-down inhibitory mechanism. Importantly, this suppression can be proactive and happen prior to stimulus onset, preventing (subsequent) attentional allocation to the distractor (Geng, 2014). This suppression may result from prior knowledge or encounter with the distractor, and/or statistical learning that can foster it (Awh et al., 2012; Failing & Theeuwes, 2018; Theeuwes, 2010). In Experiment 2, we could imagine that the cue increased preparation for the central stimulus and correspondingly sharpened proactive distractor suppression. If the distractor was shown prior to the central stimulus, it was therefore suppressed, with an effect visible in V1 at the C1 level. In comparison, when the distractor was presented following the central stimulus, attention allocation to this latter stimulus prevailed and hence (proactive) distractor suppression was not or less effective. However, according to the biased competition account (Beck & Kastner, 2005), proactive suppression should allow more resources to be available for target processing, resulting in better task performance. Behavioral results of Experiment 2 do not support this interpretation: Participants were faster in the pre- than post-central stimulus condition,

but they also missed more targets in the former condition. Hence, task performance was not simply better for the pre- than post-central stimulus condition. Moreover, a simple suppression account appears difficult to hold when one considers the fact that after the reduced C1, the P1 and subsequent ERP activities were actually larger in the pre- than post-central stimulus condition. Alternatively, an unspecific arousal effect could be surmised to account for this position effect (for the C1), as well as these behavioral results (i.e., faster RTs but lower accuracy for pre- than post-central stimulus condition). According to the arousal-biased competition (ABC) model and glutamate amplifies nor-adrenergic effects (GANE) model, arousal biases mental processing to favor high- over low-priority stimuli by enhancing activity of neurons transmitting high-priority mental representations and suppressing activity of neurons transmitting lower priority mental representations (Mather et al., 2016; Mather & Sutherland, 2011). In Experiment 2, participants could hardly predict whether the central stimulus or a peripheral distractor would appear first following the cue. Therefore, when the peripheral distractor was shown prior to the central stimulus, it could increase arousal transiently (i.e., preparedness), resulting in faster RTs for the central target (Booth et al., 2007; Fan et al., 2005; Konrad et al., 2005), but at the cost of precision however (i.e., they also missed it more often than in the post-central stimulus condition). At the ERP level, this arousal effect would lead to a lower C1 initially (gating by arousal), later followed by a P1 and N1 amplification. In comparison, when the distractor was presented after the central stimulus, arousal (driven by the peripheral distractor) was probably reduced because the processing of the central stimulus prevailed. Last but not least, predictive coding might also explain this position effect for the C1 (and P1) in Experiment 2 (see Friston & Kiebel, 2005; Jehee & Ballard, 2009; Rao & Ballard, 1999). Previous fMRI studies already showed that V1 can be the locus of predictive coding effects, which can be dissociated from the effects driven by selective attention (Kok et al., 2012). Interestingly, a previous fMRI study reported a reduction of V1 activity for unattended stimuli that were predicted (Kok et al., 2011). Translated to Experiment 2 and the C1 results, we could therefore assume that the peripheral distractor was *gated* in V1 at the C1 level when shown prior to the central stimulus because participants somehow predicted it (its occurrence) even though it was unattended (and task-unrelated). When shown after the central stimulus, the distractor led to a larger C1 component because it corresponded to a prediction error to some extent (Rauss et al., 2011). Additional ERP research is needed to assess whether this intriguing position effect found for the C1 (and P1) in Experiment 2 could be best explained by top-down suppression, arousal or predictive coding.

In sum, the results of two EEG experiments converge and show that attentional load does not influence the C1 component in a way that is compatible with the tenets of the load theory of selective attention. Instead of merely disconfirming this dominant theoretical framework, these new ERP results suggest that working memory, besides attention load, might be involved in this task, and eventually blur or mask modulatory effects of attentional load on the striate C1 (as well as extrastriate P1) component. Hence, a refined experimental design and the use of purer task demands are probably required in future EEG studies before it could be concluded with high confidence that attentional load does not influence the C1 component (see also Qin et al., 2022 for meta-analytical evidence for a modulation of this component by attentional load). Relatedly, whether or not working memory per se could account for the amplitude modulations found at the C1 (Experiment 1) and CNV (Experiment 2) levels awaits validation at the empirical level. Furthermore, an important contribution of our study is to show that besides load, variations of the C1 component by other cognitive factors can probably be found (see Experiment 2). We outline and discuss three of them (i.e., top-down suppression, arousal, or predictive coding) which appear valuable to consider in future ERP studies when the goal is to better delineate and understand top-down modulatory effects on the striate C1 component.

AUTHOR CONTRIBUTIONS

Nan Qin: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; validation; visualization; writing – original draft; writing – review and editing. **Francesca Crespi:** Data curation; investigation. **Alice Mado Proverbio:** Writing – review and editing. **Gilles Pourtois:** Conceptualization; funding acquisition; investigation; methodology; project administration; resources; software; supervision; writing – review and editing.

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DATA AVAILABILITY STATEMENT

Data are available at the Open Science Framework and can be retrieved at https://osf.io/vxcky/?view_only=88c21a2342464c34b6f60abd679f416d.

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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. The uncorrected C1 results (without subtracting the dummies) in Experiment 1. (a) Grand average ERPs for the peripheral distractor (electrodes CPz, Pz, and POz pooled together). On the ERPs, the error bar corresponds to ± 1 standard error of the mean (SEM); (b) the boxplots depict the mean C1 amplitudes during the 63–82 ms interval following stimulus onset. Each point in these boxplots represents an individual subject result, with the connecting lines showing the effect of attentional load for each SOA separately; (c) the corresponding topographical voltage map for the C1 (mean interval: 63–82 ms) in each condition is shown at the top. The two topographical maps at the bottom show the relevant C1 ERP effects (high load minus low load ERP difference) for each SOA separately.

Figure S2. The C1 results of Experiment 1 (measured at individually determined electrodes and latencies). The ERPs of the dummies were subtracted. (a) Grand average ERPs for the peripheral distractor. On the ERPs, the error bar corresponds to ± 1 standard error of the mean (SEM); (b) the boxplots depict the C1 amplitudes. Each point in these boxplots represents an individual subject result, with the connecting lines showing the effect of attentional load for each SOA separately.

Figure S3. The uncorrected C1 results (without subtracting the dummies) in Experiment 2. (a) Grand average ERPs for the peripheral distractor (electrodes CPz, Pz, and POz pooled together). On the ERPs, the error bar corresponds to ± 1 standard error of the mean (SEM); (b) the boxplots depict the mean C1 amplitudes during the 72–92 ms interval following stimulus onset. Each point in these boxplots represents an individual subject result, with the connecting lines showing the effect of attentional load for each position separately; (c) the corresponding topographical voltage map for the C1 (mean interval: 72–92 ms) in each condition is shown at the top. The two topographical maps at the bottom show the relevant

C1 ERP effects (post minus precentral stimulus ERP difference) for each load level separately.

Figure S4. The C1 results of Experiment 2 (measured at individually determined electrodes and latencies). The ERPs of the dummies were subtracted. (a) Grand average ERPs for the peripheral distractor. On the ERPs, the error bar corresponds to ± 1 standard error of the mean (SEM); (b) The boxplots depict the C1 amplitudes. Each point in these boxplots represents an individual subject result, with the connecting lines showing the effect of attentional load for each position separately.

Figure S5. The C1 results of Experiment 2 (when its peak latency was defined based on the localizer). Please note that in this analysis, the C1 from the main session peaked somewhat later than from the localizer (highlighted by the shaded area). Based on the localizer, the C1 peaked 78 ms after stimulus onset. A $-10/+10$ ms time interval around this peak latency (i.e., 68–88 ms) was used for the mean amplitude measurement performed during the main session. (a) Grand average ERPs for the peripheral distractor after subtracting the dummies. On the ERPs, the error bar corresponds to ± 1 standard error of the mean (SEM); (b) the boxplots depict the C1 amplitudes. Each point in these boxplots represents an individual subject result, with the connecting lines showing the effect of attentional load for each position separately.

Figure S6. Topographical analysis of the distractor-locked ERPs of Experiment 2. (a) The K-means analysis revealed that the C1 component was best explained by a specific

topographical map (Map #7) that was elicited in the 69–90 ms interval following peripheral distractor onset (and highlighted by the frame with dashed line). The P1 was best explained by Maps #8 and #9 during the 85–115 ms interval following peripheral distractor onset. (b) The dominant topographical maps were extracted from the segmentation of the distractor-locked ERPs in the C1 (Map #7) and P1 interval (Maps #8 and #9).

Figure S7. Topographical analysis of the cue-locked ERP data of Experiment 2. (a) For the CNV (1038–1298 ms post-cue onset, highlighted by the dotted frame), the K-means analysis revealed a different topography in the low (Map #19) compared to the high load condition (Map #20). (b) Map #19 exhibited a broader negativity along the midline than Map #20.

Table S1. Electrode and peak latency for the C1 for each participant separately.

Table S2. Electrode and peak latency for the C1 for each participant separately.

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