Neuropsychologia 172 (2022) 108283

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Spatial attention shifting to fearful faces depends on visual awareness in attentional blink: An ERP study

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ARTICLE INFO

Keywords:
Visual awareness
Spatial attention
VAN
N2pc
Attentional blink
Emotional faces

ABSTRACT

It remains unclear to date whether spatial attention towards emotional faces is contingent on, or independent of visual awareness. To investigate this question, a bilateral attentional blink paradigm was used in which lateralised fearful faces were presented at various levels of detectability. Twenty-six healthy participants were presented with two rapid serial streams of human faces, while they attempted to detect a pair of target faces (T2) displayed in close or distant succession of a first target pair (T1). Spatial attention shifting to the T2 fearful faces, indexed by the N2-posterior-contralateral component, was dependent on visual awareness and its magnitude covaried with the visual awareness negativity, a neural marker of awareness at the perceptual level. Additionally, information consolidation in working memory, indexed by the sustained posterior contralateral negativity, positively correlated with the level of visual awareness and spatial attention shifting. These findings demonstrate that spatial attention shifting to fearful faces depends on visual awareness, and these early processes are closely linked to information maintenance in working memory.

1. Introduction

In the past two decades, an increasing amount of research has been devoted to investigating how spatial attention and visual awareness are influenced by emotional stimuli such as emotional faces. A method of choice to investigate this is electroencephalography (EEG), as it allows the time course of neural activity to be distinguished by revealing the electrophysiological markers (event-related potentials or ERPs) of cognitive processes.

Using such methods, research has shown that consciously perceived emotional faces attract spatial attention. Specifically, emotional faces have been found to elicit an N2-posterior-contralateral component or the N2pc (Eimer and Kiss, 2007; Holmes et al., 2009), a component reflecting attention deployment across spatial locations and manifesting as a relative negativity appearing at about 200–300 ms after stimulus onset on posterior electrodes contralateral to the attended stimulus (e.g., Eimer, 1998; Kiss et al., 2008).

Emotional faces are not only prioritised for spatial attention, but they can also be processed without conscious awareness (Del Zotto and Pegna, 2015; Kiss and Eimer, 2008; Pegna et al., 2008, 2011). For example, using backward masking, Del Zotto and Pegna (2015) found that subliminally presented fearful faces elicited a larger N170, a face-specific ERP, than subliminal neutral faces. This finding was taken to show that fearful faces can be processed without visual awareness (Del Zotto and Pegna, 2015). Additionally, this modulating effect of subliminal fearful expressions on the N170 occurred prior to the emergence of the visual awareness negativity (VAN), the neural marker of early visual awareness (Del Zotto and Pegna, 2015). The VAN is a relative negativity that emerges when information is consciously perceived compared to when it is not, and it appears at around 200 ms post stimulus over posterior brain regions (for a review see Förster et al., 2020), reflecting an early perceptual stage of awareness (Cohen et al., 2020; Förster et al., 2020). A later stage of awareness is suggested to be reflected by the P3, a positive wave appearing at around 300–600 ms post stimulus over parietal regions. The P3 is also greater for consciously perceived stimuli compared to unconscious stimuli. However, unlike the VAN, the P3 seems to represent a reflective process of awareness that is characterised by various higher-level cognitive processes (Cohen et al., 2020; Lamme, 2003; for reviews see Polich, 2007; Railo et al., 2011).

As emotional faces appear to be prioritised by the spatial attention system and are processed without awareness, a question arises as to whether these two processes (i.e., attention and awareness) are independent of each other where emotional faces are concerned. Examinations of the relationship between awareness and spatial attention in

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https://doi.org/10.1016/j.neuropsychologia.2022.108283
Received 9 February 2022; Received in revised form 7 May 2022; Accepted 29 May 2022
Available online 2 June 2022

response to emotional faces have been carried out mainly in behavioural studies. In a seminal study, Mogg and Bradley (1999) presented subliminal emotional and neutral faces bilaterally to healthy viewers. They found that the detection of a target stimulus was faster when it was preceded by an unseen angry compared to an unseen neutral face. Similar results were since reported for subliminally presented fearful faces (e.g., Carlson and Reinke, 2010; Fox, 2002). These results showed that spatial attention may shift towards emotional faces even when they are rendered nearly invisible, leading to facilitated detection of targets presented immediately afterwards at the same location. This suggests that visual awareness is not necessary for spatial attention shifting to occur. However, the current ERP evidence has not confirmed this suggestion. Specifically, to the best of our knowledge, there have been no systematic investigations on the neural marker of spatial attention shifting, the N2pc, to emotional faces under varied conditions of visual awareness.

In the current study we used the attentional blink (AB) to examine brain activity under different conditions of visual awareness. The AB is a phenomenon where the second of two targets presented in rapid succession is poorly identified if it appears very shortly after the first target (e.g., 100–500 ms; Broadbent and Broadbent, 1987; Shapiro et al., 1997). The requirement of attending to the first target (T1) is thought to attenuate the processing of the second target (T2), thereby suppressing awareness of it (for a review see Martens and Wyble, 2010).

Previous AB studies have found that the ERP signals associated with T2 in the VAN and P3 time windows correlated with participants' awareness of this target. Specifically, an ERP negativity between 200 and 300 ms was found for successfully detected, compared to undetected T2s (Sergent et al., 2005), which is consistent with a VAN that reflects early perceptual awareness (Eklund and Wiens, 2018; Sergent et al., 2005). Similarly, the P3 was found to be absent for undetected T2s (Martens and Wyble, 2010), showing that the later, reflective process of awareness of the stimulus can also be suppressed during the AB. However, the P3 is also reported to decrease with greater working memory load, and this has been suggested to reflect poor information encoding (Morgan et al., 2008; Studer et al., 2010). Therefore, some authors have suggested that the P3 reflects information encoding (e.g., Craston et al., 2009; Vogel and Luck, 2002), rather than awareness *per se* (e.g., Pitts et al., 2014; Railo et al., 2011). Another relevant neural marker in AB research is the sustained posterior contralateral negativity (the SPCN), a late contralateral negativity at posterior brain regions, which has been linked to the consolidation of perceptual information in working memory (Luria et al., 2016). Previous AB studies, particularly those using lateralised stimuli, have shown that the SPCN elicited by T2s can be reduced when they were presented after a short T1-T2 lag, compared to a longer one (Jolicœur et al., 2006a, 2006b; Pomerleau et al., 2014), and when the working memory load was increased (Dell'Acqua et al., 2006; Robitaille et al., 2007). It has been suggested that the reduced SPCN reflects a weaker consolidation in working memory of T2 stimuli when they are presented during the AB (Jolicœur et al., 2006a).

By using a bilateral AB presentation paradigm, it is possible to investigate spatial attention shifts and hence the N2pc to lateral targets, under different conditions of awareness (Dell'Acqua et al., 2006; Jolicœur et al., 2006a, 2006b). For example, Jolicœur et al. (2006b) presented participants with a rapid stream of letters centrally, in which a single digit would appear as T1. A pair of digits (T2) would then appear after T1 with either a short or long lag. The N2pc was found to be substantially reduced in short compared to long lag conditions and was completely absent during the attentional blink. These results showed that the N2pc can be modulated by the level of visual awareness (Jolicœur et al., 2006b). However, T1 and the distractors were presented at spatially separate locations from the T2 in this study (Jolicœur et al., 2006b), which has been reported to increase the AB (e.g., Du et al., 2011; Jefferies et al., 2007; Jefferies and Di Lollo, 2009; Juola et al., 2004; Olivers, 2004; but see Kristjánsson and Nakayama, 2002). It is unclear whether an N2pc would be similarly evoked and modulated by visual awareness in the absence of a spatial separation between succeeding stimuli. Moreover, the results of Jolicœur et al. (2006b) may not generalise to all stimuli. For instance, the AB is largely attenuated or even absent with emotional human faces as T2 (e.g., Darque et al., 2012; Luo et al., 2010; Müsch et al., 2012), possibly because the processing of emotional stimuli may rely on a rapid subcortical pathway to the amygdala (LeDoux, 2000; Öhman, 2005). Whether the ERP results reported in previous bilateral AB studies apply in the case of emotional faces has not been established.

The current ERP study aimed to address the question of whether attention and awareness are necessarily coupled or independent, by examining spatial attention shifting to fearful faces in a bilateral AB paradigm where there was no spatial separation between succeeding stimuli. The paradigm contained two types of blocks. In T1-report blocks, participants were asked to indicate the gender of T1 faces, as well as the visibility and side of the fearful face in T2. In T1-ignore blocks, identical stimuli were presented but participants were instructed to ignore T1 and only respond to T2. In all blocks, a T2 was presented after T1 either with a short lag or with a long lag.

We predicted that, in the case of fearful faces, if spatial attention shifting depends on visual awareness, the amplitude of the N2pc, indexing spatial attention shifting, would be reduced when awareness is limited (i.e., the short lag condition compared to the long lag condition, and the T1-report condition compared to the T1-ignore condition). We would also expect a positive correlation between the N2pc and the VAN, which indexes perceptual awareness. Additionally, we were interested in exploring the relationships among these two neural markers and the neural indicators of reflective awareness (the P3) and information consolidation in working memory (the SPCN).

2. Method

2.1. Participants

The sample size was determined based on a previously reported effect of T1-T2 lag on the N2pc (estimated $\eta_p^2 = 0.43$; Jolicœur et al., 2006b). For our main 2 (T1-T2 lag: short, long) X 2 (task type: T1-ignore, T1-report) X 2 (laterality: contralateral, ipsilateral) repeated-measures ANOVAs, a sample size of 16 was necessary to obtain a significant main effect of T1-T2 lag that is sufficiently powered (i.e., 90%), with an effect size of 0.43 at an alpha level of 0.05, two tailed (calculated with MorePower Software; Campbell and Thompson, 2012).

Twenty-nine participants with normal or corrected-to-normal vision from the University of Queensland were recruited and were compensated with course credits for their participation in the experiment. Participants had no history of neurological or psychiatric conditions. Three participants were excluded because they did not provide sufficient data (see EEG recording and pre-processing). The final sample therefore consisted of data from 26 participants ($M_{age} = 21.3$ years, $SD_{age} = 2.7$ years; 12 males, 14 females; 25 right-handed). The experimental procedure was approved by the ethics committee at the University of Queensland. All participants provided informed consent for their participation.

2.2. Apparatus and stimuli

All stimuli were presented on a 24-inch ASUS LCD monitor model VG248QE (resolution: 1920 × 1080 pixels; refresh rate: 144 Hz) placed 70 cm away from the participant's eyes. A Dell MOCZUL mouse and a Dell KB522p keyboard were used to record responses. PsychoPy3 (Peirce et al., 2019) was used to present stimuli.

The face stimuli used in this experiment were obtained from the Karolinska Directed Emotional Faces Database (Goeleven et al., 2008). We selected face images with happy and neutral expressions from 16 models (8 males, 8 females) for T1 stimuli (happy faces) and distractors (neutral faces). Face images with fearful and neutral expressions from a different set of models (6 males, 6 females) were used for T2 stimuli. We cropped the face images into an oval shape of 8 cm × 6.2 cm (6.5° × 5.1° in visual angle) to keep only the facial information of each image. All images were converted to grey-scale. However, to distinguish T1 stimuli from the other stimuli in the streams, T1 happy faces were further tinted in red by increasing the RGB red channel by 150% (see Fig. 1a; Müsch et al., 2012). All image editing was done in Photoshop 2021).

Face images were presented bilaterally with the centre of each face positioned 5 cm (4.1° in visual angle) to the left or right of a central fixation cross on the screen. Each T1 presentation consisted of two upright happy face stimuli of a same model (Fig. 1a), and each distractor presentation consisted of two upside-down neutral faces of a same model (Fig. 1b). We used upside-down neutral faces as distractors in order to obtain a high similarity between targets and distractors while ensuring that the target stimuli can be distinguished from the distractors (Müsch et al., 2012). Each T2 presentation consisted of an upright fearful face and an upright neutral face from a same model (Fig. 1c). For each T2 presentation, the fearful face was either on the left or right side of the screen with a neutral face on the other side. All stimuli were presented on a black screen.

2.3. Procedure

As shown in Fig. 2, each trial started with a fixation screen of a variable duration between 500 and 800 ms, which was followed by two bilateral rapid streams of faces. The streams consisted of ten pairs of faces, each presented for 150 ms with no interstimulus interval between two successive pairs. A pair of red happy faces (T1) was presented at position 3 in the streams. A pair of black-and-white faces that contained a fearful face on either side of the screen (T2) was presented either at position 4 (lag 1/short lag condition; 150 ms post-T1-onset) or position 8 (lag 5/long lag condition; 750 ms post-T1-onset). Distractors (a pair of upside-down neutral faces) were presented at all other positions. In the T2-absent control trials, distractors were presented at position 4 and 8 instead. After all the ten face pairs were presented, a fixation screen was shown for 600 ms. Then, participants were asked to respond to either two or three questions depending on the blocks. In *T1-report blocks*, participants were asked to indicate the gender of T1 by pressing Q (male) or W (female) keys on the keyboard and then rate the visibility of T2 by using the mouse to click on one of the four rating points on the screen (1 = *No experience*, 2 = *Brief glimpse*, 3 = *Almost clear image*, 4 = *Absolutely clear image*). Immediately afterwards, they were asked to indicate on which side of the screen the fearful face had appeared (left mouse button = *appeared left*, right mouse button = *appeared right*). In *T1-ignore blocks*, participants were told to ignore T1 and only respond to T2. Consequently, participants only performed the visibility rating and the fearful face location task in this sequence. In T2-absent trials, participants performed the same tasks as in T2-present trials without being explicitly informed of the absence of T2. A blank screen of 500 ms was presented before the next trial began. On average, each trial took approximately 6 s.

In each trial, the gender of T1 and T2 images were either the same or different. Participants were instructed to fixate at the screen centre unless they needed to move their eyes during the visibility rating. They were instructed to respond as accurately as possible after the question cue appeared on the screen. In T1-report condition, they were instructed to prioritise their accuracy in the T1 gender task. Participants completed two T1-report blocks and two T1-ignore blocks in a randomised order. There were in total 240 short lag trials, 240 long lag trials and 120 T2-absent trials, randomly intermixed within each block. Participants were allowed short breaks between blocks. Each block took on average 7.4 min (*SD* = 1.0 min) and the whole experiment took approximately 65.7 min (*SD* = 9.4 min).

2.4. EEG recording and pre-processing

Continuous EEG was recorded at 1024 Hz using the BioSemi ActiveTwo system (Biosemi, Amsterdam, Netherlands) with 64 electrodes placed according to the international 10–20 system. Recordings were referenced to the CMS/DRL electrodes (www.biosemi.com). A pair of bipolar electrodes was used to record horizontal electrooculogram (EOG). An additional electrode was placed below the left eye of the participants and was used in conjunction with FP1 to record vertical EOG.

Pre-processing of the EEG data was performed with EEGLAB (Delorme and Makeig, 2004) and ERPLAB (Lopez-Calderon and Luck, 2014). We interpolated individual electrodes that produced sustained noise throughout the experiment.[1] Signals were re-sampled to 512 Hz offline, filtered from 0.1 to 30 Hz and re-referenced to the average of all electrodes. A notch filter of 50 Hz was included to remove line noise. EEG signals were segmented into epochs with a time window of 800 ms from the onset of T2, relative to a pre-stimulus baseline (−100 to 0 ms). Trials with artefacts of eye blinks and eye movements were semi-automatically detected and removed on a trial-by-trial basis, with a threshold of −100 to 100 μV. Trials with other artefacts were detected and removed semiautomatically using a threshold of −80 to 80 μV. After artefact rejection, data from three participants were excluded[2] from further analyses due to the limited number of remaining epochs (i.e., less than 40 epochs per experimental condition), resulting in a final sample size of 26 participants. For the remaining participants, the following number of ERP epochs were contained in each condition averaged across participants: short lag T1-ignore (*M* = 108, *SD* = 10), short lag T1-report (*M* = 109, *SD* = 8), long lag T1-ignore (*M* = 101, *SD* = 14), long lag T1-report (*M* = 103, *SD* = 12) after artefact rejection.

To obtain the ERP responses to T2, we subtracted the average signals of T2-absent trials, time-locked at position 4 (short lag condition) and position 8 (long lag condition), from the average signals of the corresponding T2-present trials for different task type conditions. For example, to obtain T2-specific signals in the short-lag T1-report condition, we subtracted ERPs from the T2-absent trials in T1-report blocks, time-locked at position 4, from ERPs from the short-lag T1-report condition. All ERP data analyses were performed on the T2-specific signals.

2.5. Data analysis

2.5.1. Behavioural data

As the participants were instructed to respond only after they saw the question prompt, we did not analyse their reaction time data. By contrast, accuracy on both the T1 gender task and the T2 fearful face location task, as well as visibility ratings were analysed.

2.5.2. ERP amplitudes

VAN. To extract the VAN for T2 stimuli, we subtracted the T2 ERPs in T1-report trials (short lag), where awareness of T2 was restricted, from T1-ignore trials (short lag), where awareness of T2 should be less limited (VAN-T2). In addition, to extract the VAN directly related to the AB (VAN-AB), we subtracted short lag trials from long lag trials, regardless of task types. To identify electrodes for both VAN-T2 and VAN-AB, we performed a Mass Univariate Analysis over all electrodes and time-points (0–800 ms post-stimulus) for significant differences (two-tailed family-wise α = 0.05) using a cluster-based permutation test (2500 permutations) to control for multiple comparisons (Groppe et al., 2011). The Mass Univariate Analysis was performed using the Mass Univariate ERP Toolbox in Matlab (https://openwetware.org/wiki/Ma

[1] Two of the 26 participants in the final sample necessitated the interpolation of two electrodes.

[2] Results of all the analyses revealed the same effects when including these excluded participants (*N* = 29).

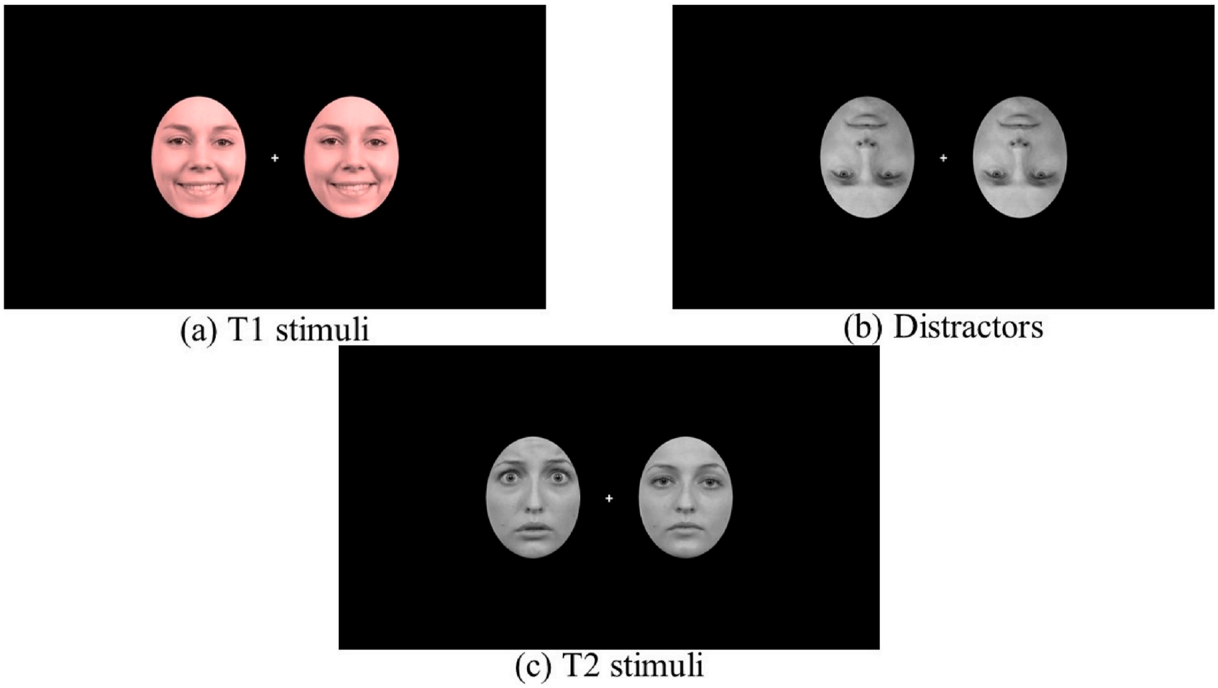

Fig. 1. (a) Examples of T1 stimuli (a pair of red happy faces), (b) distractors (a pair of upside-down black-and-white neutral faces) and (c) T2 stimuli (a fearful face and a neutral face in black-and-white). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

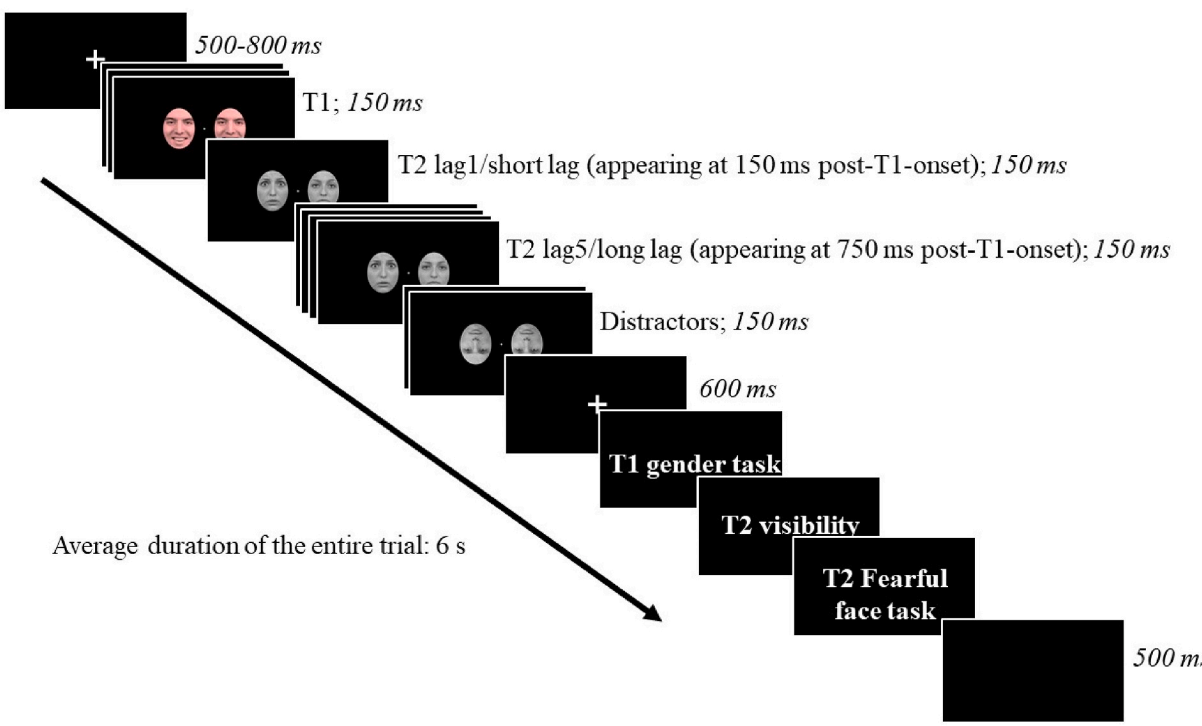

Fig. 2. Time-course of events during a trial of the full experimental procedure.

ss_Univariate_ERP_Toolbox). Electrodes were considered spatial neighbours if they were within approximately 3.9 cm of one another, resulting in each electrode with on average 3.7 spatial neighbours (Groppe et al., 2011), and the cluster formation threshold was set at 0.05. Significant differences between conditions (i.e., a significant negative cluster) were found on electrodes TP7/8, P1/2, P3/4, P5/6, P7/8, P9/10, PO7/8 and PO3/4. We therefore pooled and exported the mean amplitudes from these electrodes between 200 and 300 ms for the analyses of the VAN.

N2pc. An N2pc to the fearful face would manifest as an effect of laterality (a negativity towards signals contralateral to the fearful face, compared to ipsilateral signals) on data exported from the VAN time window. We kept the time windows and electrodes the same for the VAN and the N2pc to avoid any potential spurious finding resulting from selecting different electrodes and/or time windows. We then obtained the N2pc difference waves by subtracting signals ipsilateral to the side of the fearful face from the contralateral signals, collapsing across the side of the fearful face.

P3. A Mass Univariate Analysis (corrected for multiple comparisons using cluster-based permutation test) on data averaged across all conditions revealed a significant positive cluster in a common time window 400–700 ms post stimulus at CPz, Pz, POz, CP1/2, CP3/4, P1/2, P3/4, P5/6 and PO3/4. We thus pooled data from these electrodes and exported the mean amplitudes between 400 and 700 ms for the analyses of the P3.

SPCN. We obtained the SPCN difference waves by subtracting signals ipsilateral to the side of the fearful face from the contralateral signals at posterior electrodes (i.e., P7/8, P9/10, and PO7/8; Eimer and Kiss, 2010; Luria et al., 2010), collapsing across the side of the fearful face. By focusing on the SPCN time window (i.e., 400–800 ms) of the difference waves across all participants, we found negative slow waves in all conditions at these electrodes. We thus pooled data from these electrodes and exported the mean amplitudes between 400 and 800 ms for the analyses of the SPCN.

All statistical analyses were performed in IBM SPSS Statistics 27.

3. Results

3.1. Behavioural results

3.1.1. T1 gender task

Participants' accuracy (the proportion of correct responses) in the T1 gender task was submitted to a one-way (T1-T2 lag: short, long, T2-absent) repeated-measures ANOVA. A main effect of the lag was found, F (1, 25) = 12.71, $p < .001$, $\eta_p^2 = 0.34$. Follow-up comparisons using Bonferroni correction showed that participants were significantly less accurate in the short lag condition ($M = 0.82$, $SD = 0.10$) than when the lag between T1 and T2 was long ($M = 0.86$, $SD = 0.11$), $p = .009$, and when there was no T2 ($M = 0.87$, $SD = 0.10$), $p < .001$. No significant difference was found between the T2-absent and the long lag conditions, $p = 1$.

3.1.2. T2 fearful face location task

Participants' accuracy at the fearful face location task (T2 task) was submitted to a 2 (T1-T2 lag: short, long) X 2 (task type: T1-ignore, T1-report) repeated-measures ANOVA. Participants were significantly less accurate in the short lag condition ($M = 0.82$, $SD = 0.12$), compared to the long lag condition ($M = 0.88$, $SD = 0.12$), F (1, 25) = 20.88, $p < .001$, $\eta_p^2 = 0.46$. Participants' performance was also worse in the T1-report condition ($M = 0.81$, $SD = 0.13$), compared to the T1-ignore ($M = 0.89$, $SD = 0.12$), F (1, 25) = 18.68, $p < .001$, $\eta_p^2 = 0.43$. The interaction between lag and task type was significant, F (1, 25) = 5.65, $p = .025$, $\eta_p^2 = 0.18$. Follow-up t-tests showed that the effect of lag described above was significant in both the T1-report condition (Mean Difference = 0.08), t (25) = 3.75, $p = .001$, $d = 0.74$, and the T1-ignore condition (Mean Difference = 0.03), t (25) = 3.95, $p = .001$, $d = 0.78$.

We also examined T2 accuracy conditional on T1 accuracy in the T1-report condition. A paired-sample t-test showed that, in trials where participants were correct at the T1 gender task, they were significantly worse at the T2 task in the short lag condition ($M = 0.77$, $SD = 0.14$) than the long lag condition ($M = 0.86$, $SD = 0.15$), t (25) = 3.84, $p = .001$, $d = 0.75$.

3.1.3. T2 visibility rating

We analysed the T2 visibility ratings as a manipulation check for the two independent variables (task type and T1-T2 lag). As the distribution of responses to the four-point visibility rating was rather uneven due to largely variable response patterns across participants, we ran a Linear Mixed-effects Model analysis on all available datapoints on a trial-by-trial basis. The restricted maximum likelihood method was used to estimate model parameters and Satterthwaite approximations were used for the degrees of freedom (Luke, 2017). To account for between-participant variance, we included participant as a random factor (West, 2009). T1-T2 lag and task type were entered as fixed factors into the model. Results showed that both T1-T2 lag (F (1, 12669) = 557.32, $p < .001$) and task type (F (1, 12669) = 756.18, $p < .001$) were significant predictors of visibility ratings. Specifically, participants rated T2 to be more visible in the long lag condition, compared to the short lag, $\beta = 0.26$, $SE = 0.01$, $p < .001$. They also rated T2 as more visible in the T1-report condition, compared to T1-ignore, $\beta = 0.31$, $SE = 0.01$, $p < .001$.

3.1.4. T2-absent trials

A one-way repeated-measures ANOVA on the T2 visibility ratings in T2-absent control trials showed that participants responded significantly more often "No experience" or "Brief glimpse" to the possible presence of a T2, compared to the other two visibility rating points ($ps < .001$, Bonferroni corrected). Moreover, in the T2-absent trials, responses about the location of the fearful face were equally likely on the left and on the right, t (25) = 1.01, $p = .323$.

3.2. ERP results

In our ERP analyses, we included data from all available trials without conditionalising on T1 accuracy. This is because we were interested in comparing the ERPs across all four conditions from the experimental design (short/long-lag T1-report/T1-ignore) and we have shown that large differences in T2 accuracy were present across these conditions, regardless of T1 accuracy.

3.2.1. VAN and N2pc time window (200–300 ms)

To examine the neural correlate of perceptual awareness, we analysed the mean amplitudes over the waveforms in the VAN time window (200–300 ms), see Fig. 3. We ran a 2 (T1-T2 lag: short, long) X 2 (task type: T1-ignore, T1-report) X 2 (laterality of the fearful face as referred to electrodes: contralateral, ipsilateral) repeated-measures ANOVA, collapsed across left and right electrodes. Significant differences between the lag conditions reflected more negative amplitudes when T2 was presented after a long lag from T1 ($M = -1.06$ μV, $SD = 1.50$) than in the short lag condition ($M = -0.29$ μV, $SD = 0.77$), F (1, 25) = 12.19, $p = .002$, $\eta_p^2 = 0.33$. The main effect of task type was also significant, F (1, 25) = 15.78, $p < .001$, $\eta_p^2 = 0.39$, with the T1-ignore condition showing significantly more negative amplitudes ($M = -1.03$ μV, $SD = 1.42$) than the T1-report condition ($M = -0.32$ μV, $SD = 0.78$). Importantly, we found a significant main effect of laterality, F (1, 25) = 35.06, $p < .001$, $\eta_p^2 = 0.58$, in that negative deflections contralateral to the fearful face ($M = -1.13$ μV, $SD = 1.36$) were significantly larger than those ipsilateral to the fearful face ($M = -0.21$ μV, $SD = 0.82$), reflecting an effect of the N2pc. No other effect was significant, $Fs < 4.05$, $ps > .055$.

To confirm that the above effects were not affected by saccadic eye movements towards one or the other face stream, we examined the horizontal EOG signals following T2 presentations. The horizontal EOG signals were calculated by subtracting the mean signals evoked by T2 presentations on the right EOG from those on the left EOG, separately for trials where the T2 fearful face was on the left and trials where the fearful face was on the right. One-sample t-tests showed that there was no shift in the horizontal EOG signals when the fearful face was on the left, t (25) = 1.88, $p = .072$, or when the fearful face was on the right, t (25) < 1, $p = .380$, indicating that no eye movements arose following the presentations of T2.

Furthermore, we performed the 2 (T1-T2 lag: short, long) X 2 (task type: T1-ignore, T1-report) X 2 (laterality of the fearful face as referred to electrodes: contralateral, ipsilateral) repeated-measures ANOVA separately for the left and right hemisphere electrodes. We found significant main effects of laterality for both the left, F (1, 25) = 32.55, $p < .001$, $\eta_p^2 = 0.57$, and the right electrodes, F (1, 25) = 24.49, $p < .001$, $\eta_p^2 = 0.50$, such that signals were more negative when the fearful face was contralateral to the electrodes, compared to when it was ipsilateral to

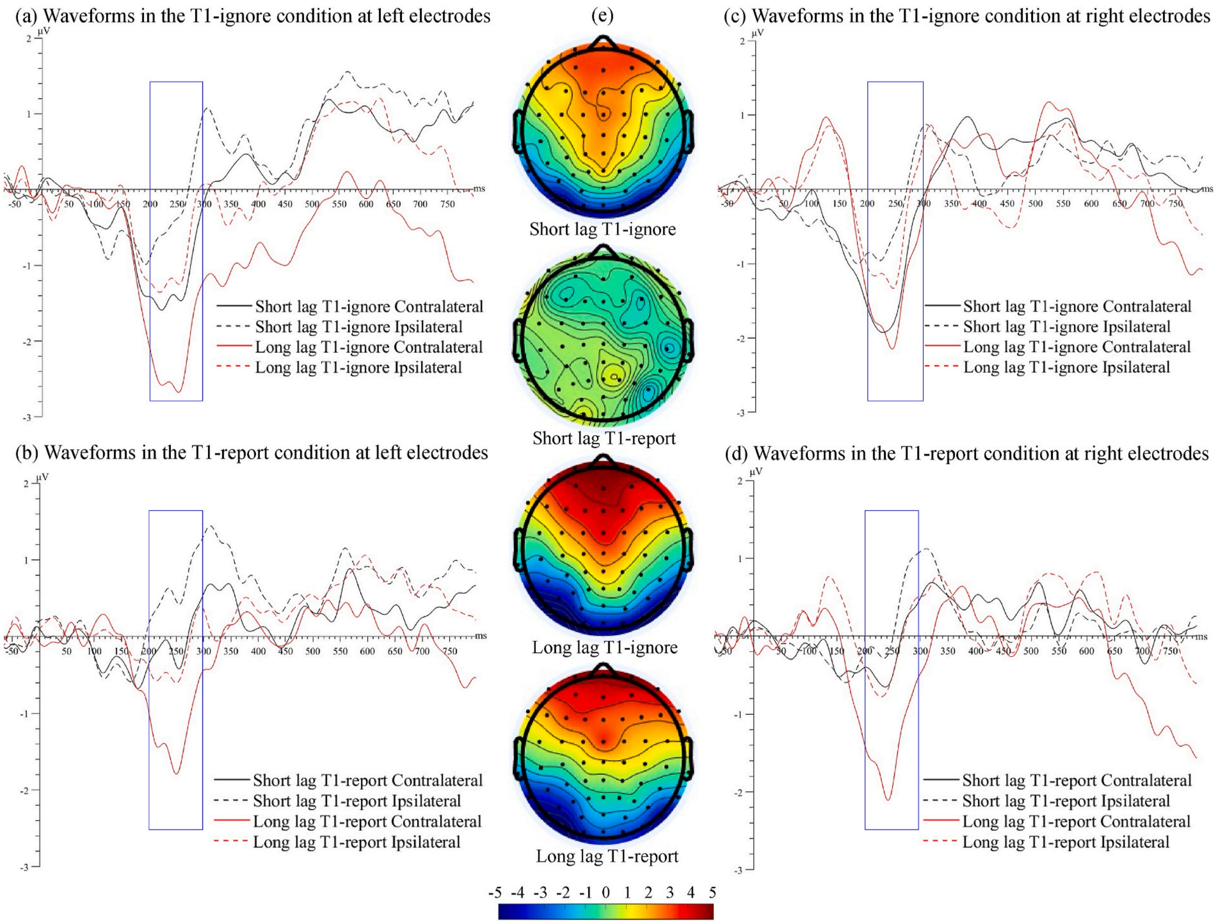

Fig. 3. Contralateral and ipsilateral waveforms in (a) T1-ignore and (b) T1-report conditions for the left electrodes (pooled from TP7, P1, P3, P5, P7, P9, PO7, PO3) and (c) T1-ignore and (d) T1-report conditions for the right electrodes (pooled from TP8, P2, P4, P6, P8, P10, PO8, PO4) for the VAN time window (200–300 ms). The middle panel (e) shows the topographic maps for all combinations of task types and lags (short lag T1-ignore, short lag T1-report, long lag T1-ignore, long lag T1-report).

the electrodes, see Fig. 3a–d. These results showed that the N2pc was present for both the left and right hemisphere electrodes.

Taken together, these results showed that fixation was generally maintained at the screen centre throughout the experiment, and that the fearful face in T2 was always lateralised to either the left or right hemisphere electrodes, excluding the eventuality that participants may have carried out the experiment focusing solely on one of the two visual streams.

To further investigate the differences among the N2pcs in various conditions, we calculated the N2pc difference waves for all four combinations of task types and lags (short lag T1-ignore, short lag T1-report, long lag T1-ignore, long lag T1-report; see Fig. 4a) by subtracting signals ipsilateral to the fearful face from the contralateral signals. We ran one-sample *t*-tests and found that all N2pcs were significantly different from 0, $ts > 4.20$, $ps < .001$, $ds > 0.82$. This result showed that the N2pc, an indicator of spatial attention shifting, was observed in all conditions. In order to compare the N2pcs across varied conditions of awareness, we submitted the amplitudes of the N2pcs to a 2 (T1-T2 lag: short, long) X 2 (task type: T1-ignore, T1-report) repeated-measures ANOVA and followed up the interaction between task type and T1-T2 lag despite its non-significance ($p = .133$). Simple effect tests showed that the N2pc in the short lag T1-report condition ($M = -0.59$ μV, $SD = 0.72$) was significantly smaller in amplitude than the N2pc in the long lag T1-report condition ($M = -1.05$ μV, $SD = 1.18$), $p = .040$, and the N2pc in the short lag T1-ignore condition ($M = -1.00$ μV, $SD = 1.02$), $p = .028$. These results showed that the magnitude of the N2pc was smaller when visual awareness was limited (i.e., short lag T1-report condition), compared to when it was less restricted.

To assess whether spatial attention shifting and perceptual awareness were correlated, we calculated the VAN-T2 (short lag T1-ignore minus short lag T1-report conditions) and VAN-AB (long lag minus short lag conditions) and performed Pearson's correlation analyses between the overall N2pc (averaged across all four conditions) and both VANs. Results showed that the amplitudes of the overall N2pc were significantly and positively correlated with the VAN-T2, $r = 0.64$, $p < .001$, and with the VAN-AB, $r = 0.51$, $p = .008$. These results showed that spatial attention shifting (indexed by the N2pc) to fearful faces was stronger when the level of visual awareness (indexed by the VAN) was higher.

3.2.2. P3 time window (400–700 ms)

To examine the neural correlate of reflective awareness, we performed a 2 (T1-T2 lag: short, long) X 2 (task type: T1-ignore, T1-report) repeated-measures ANOVA on the mean P3 amplitudes (400–700 ms), see Fig. 5. A significantly more positive P3 was found in the T1-ignore condition ($M = 1.83$ μV, $SD = 1.34$), compared to the T1-report condition ($M = 1.07$ μV, $SD = 1.00$), $F(1, 25) = 12.90$, $p = .001$, $\eta_p^2 = 0.34$. A significant interaction between task type and lag ($F(1, 25) = 7.59$, $p = .011$, $\eta_p^2 = 0.23$) was found. Post-hoc analyses showed that the significant interaction was due to a larger P3 in the T1-ignore condition ($M = 2.04$ μV, $SD = 1.55$) compared to the T1-report condition ($M = 0.87$ μV, $SD = 1.40$), only when T2 was presented at a short lag ($p < .001$). The effect of task type was not found in the long lag condition ($p = .181$).

The mean P3 amplitudes did not correlate with any other ERP

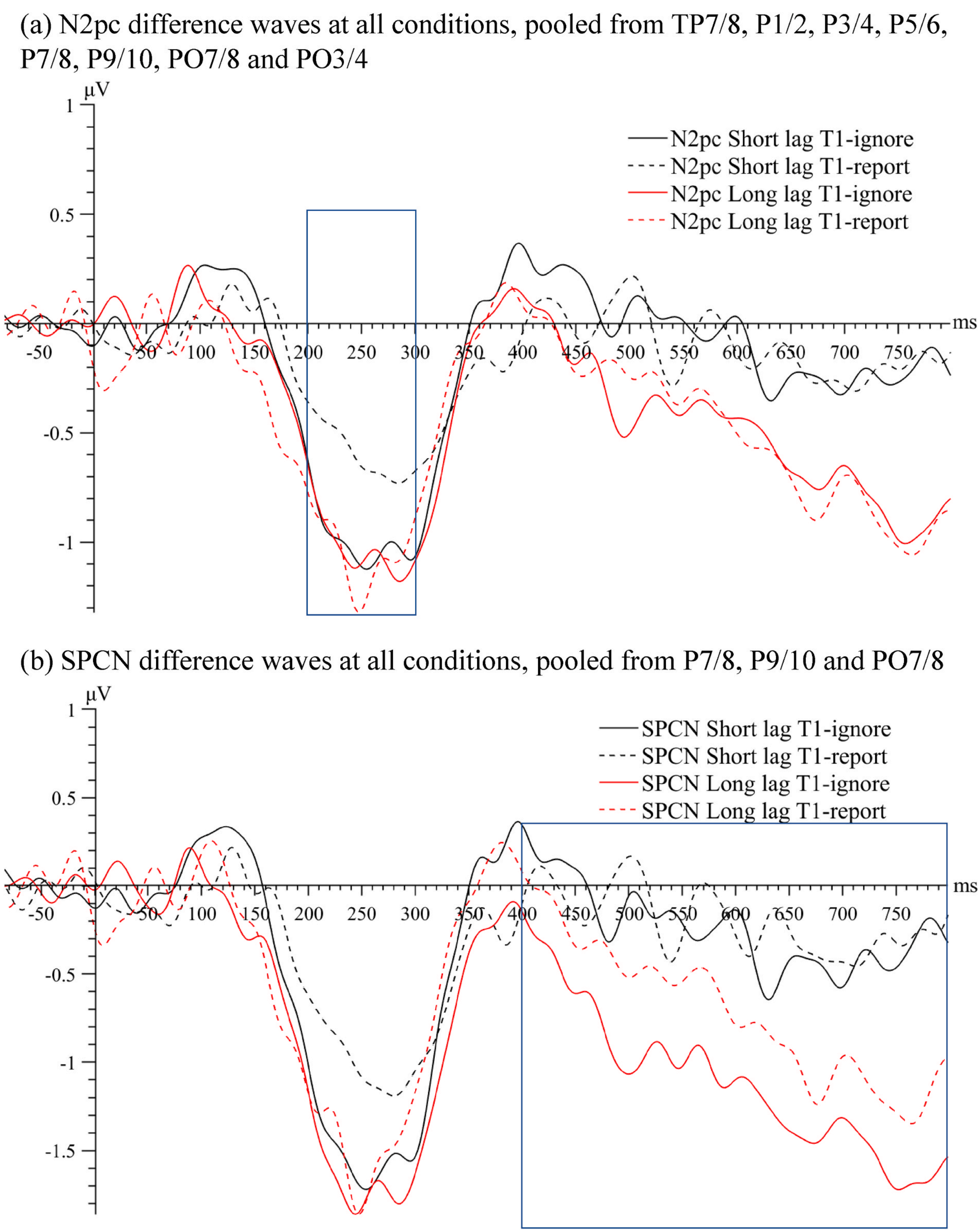

Fig. 4. (a) N2pc difference waves (contralateral minus ipsilateral signals), collapsed across left (pooled from TP7, P1, P3, P5, P7, P9, PO7, PO3) and right electrodes (pooled from TP8, P2, P4, P6, P8, P10, PO8, PO4), and (b) SPCN difference waves (contralateral minus ipsilateral signals) pooled from P7/8, P9/10 and PO7/8, for all conditions (short lag T1-ignore, short lag T1-report, long lag T1-ignore, long lag T1-report).

component examined in this study (all *ps* > .528).

3.2.3. *SPCN time window (400–800 ms)*

To examine whether and to what extent the consolidation of information in working memory may be affected by awareness and attention, we also examined the SPCN. We performed a 2 (T1-T2 lag: short, long) X 2 (task type: T1-ignore, T1-report) X 2 (laterality of the fearful face as referred to electrodes: contralateral, ipsilateral) repeated-measures ANOVA on the mean amplitudes of the SPCN time window (400–800 ms), collapsed across left and right electrodes. A main effect of laterality was found, F (1, 25) = 23.40, p < .001, η_p^2 = 0.48, in that signals contralateral to the fearful face (M = −0.93 μV, SD = 1.07) were significantly more negative than ipsilateral signals (M = −0.35 μV, SD = 1.07), reflecting the SPCN. The main effect of lag was non-significant, F

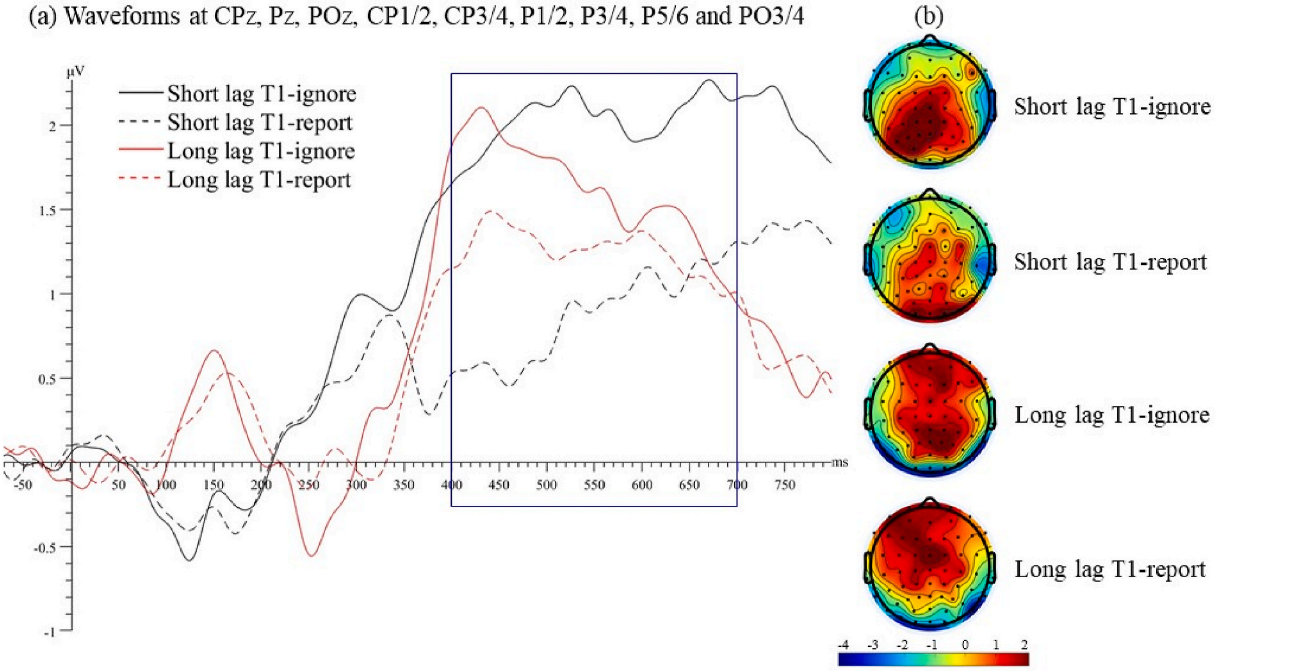

Fig. 5. (a) Waveforms in all conditions, pooled from CPz, Pz, POz, CP1/2, CP3/4, P1/2, P3/4, P5/6 and PO3/4, reflecting the P3 (400–700 ms). (b) Topographic maps for all conditions (short lag T1-ignore, short lag T1-report, long lag T1-ignore, long lag T1-report).

$(1, 25) = 4.14$, $p = .053$. However, the long lag condition showed slightly more negative ERP signals ($M = -0.98$ μV, $SD = 1.59$), compared to the short lag condition ($M = -0.30$ μV, $SD = 1.02$). A significant interaction between lag and laterality was also found, F (1, 25) $= 18.18$, $p < .001$, $\eta_p^2 = 0.42$, see Fig. 4b. Follow-up simple effect tests showed that a significant SPCN was found only in the long lag condition (Mean Difference = 0.92, $p < .001$), and not in the short lag condition (Mean Difference = 0.22, $p = .102$). No other effect was significant, $Fs < 2.50$, $ps > .126$.

We performed Pearson's correlation analyses between the SPCN averaged across all conditions and the VANs. Results showed that the amplitudes of the SPCN significantly and positively correlated with the VAN-T2 ($r = 0.44$, $p = .026$), showing that a higher level of visual awareness (due to reduced task demands) was associated with a stronger consolidation of perceptual information. A larger SPCN was also associated with a larger VAN-AB though this correlation was non-significant ($r = 0.35$, $p = .084$). A significant positive correlation between the overall N2pc and the SPCN was also found ($r = 0.65$, $p < .001$), showing that spatial attention shifts towards the target stimulus were associated with a greater consolidation of the stimulus.

3.3. T2 task accuracy and ERPs

In order to examine the relationship between the ERP components and behavioural outcomes (i.e., T2 task accuracy), we ran Pearson's correlation analyses between participants' average accuracy on the T2 task and the amplitudes of the components investigated (i.e., VAN-T2, VAN-AB, N2pc, P3 and SPCN). Results showed that the mean P3 amplitudes were positively correlated with participants' accuracy ($r = 0.40$, $p = .041$), however the effect was not significant based on a Bonferroni adjusted significance threshold (i.e., an alpha level of 0.01). No other significant correlation was found ($ps > .069$).

4. Discussion

In the current study, we presented participants with rapid serial streams of human faces and asked them to respond to two target face pairs that were displayed in close (short lag) or distant (long lag) temporal succession. Results were compared to a condition where participants responded only to the second pair of target faces (T2) while ignoring the first target (T1).

4.1. VAN and N2pc

From the Mass Univariate Analysis, we identified the VANs at posterior brain areas in the time window of 200–300 ms. Specifically, ERPs in this time window were found to be more negative when visual awareness occurred, compared to when it was diminished either due to the AB (VAN-AB) or increased task demands (VAN-T2). This finding aligns with previous AB studies where more negative EEG signals have been found for seen compared to unseen T2s in similar time windows (Eiserbeck et al., 2021; Sergent et al., 2005). The VAN has been suggested to be an indicator of the early perceptual awareness and is less susceptible to other confounding cognitive processes (Koivisto and Grassini, 2016), in contradistinction to the P3, which is characterised by a wide range of post-perceptual processes that may not be related to awareness (Pitts et al., 2014; Polich, 2007).

Crucially, we found significant N2pcs in all conditions between 200 and 300 ms, showing that spatial attention was consistently shifted towards the target fearful faces, regardless of the level of awareness. However, the N2pc amplitudes were much smaller when visual awareness was extremely restricted (short lag T1-report), compared to the less limited conditions. Moreover, higher VAN amplitudes were associated with increased N2pc amplitudes in our study. These results suggest that spatial attention shifting towards a fearful face depends on early perceptual awareness. Consistent with this, previous studies have found that the N2pc was greatly reduced (e.g., Bola et al., 2021; Qu et al., 2017; Scrivener et al., 2019) or even absent (e.g., Boncompte and Cosmelli, 2018; Busch et al., 2010; Crouzet et al., 2017; Qiu et al., 2022) when awareness of the visual stimuli was low. For example, using the change blindness paradigm, Scrivener et al. (2019) found that the N2pc for correctly localised changes was larger than the N2pc for merely sensed changes (reporting a change without localising it). Moreover, no N2pc was found for unseen changes (Scrivener et al., 2019).

Similarly, in a previous AB experiment using bilateral presentations of T2s, the N2pc decreased when participants were required to report T1, compared to when they ignored T1, especially when the T1-T2 lag was short (Jolicœur et al., 2006b). Note that in this study, the distractors and T1 were presented centrally in a single stream. As a result, the bilateral T2 stimuli were presented at distinct spatial locations from the central distractors and T1. When a T2 is both spatially and temporally distinct from other stimuli, spatial attention shifting may be facilitated, potentially accounting for the findings. Indeed, in this previous paradigm, the amplitudes of the N2pc did not differ between task type conditions (Jolicœur et al., 2006b). Specifically, the N2pc in the short lag T1-report was comparable to that in the short lag T1-ignore, showing that spatial attention to the target was equally strong in both conditions (Jolicœur et al., 2006b). Contrasting with this study, we presented all stimuli laterally, in the same two spatial locations. Using this procedure, we found that, when no changes in spatial locations of successive stimuli are present to potentially facilitate the detection of T2, spatial attention shifting can still be efficiently elicited by fearful faces in an AB paradigm. Additionally, we found that the N2pc in short lag T1-report was significantly weaker than the N2pcs in other conditions where awareness was less restricted (e.g., short lag T1-ignore), which is different from the previous finding (Jolicœur et al., 2006b).

Our finding that spatial attention shifting to fearful faces depends on the level of visual awareness is consistent with the recurrent processing model (Lamme, 2003). According to this model, visual information goes through multiple processing stages (i.e., feedforward and feedback processes) before it reaches perceptual awareness and, depending on the level of processing, attracts spatial attention (Lamme, 2003, 2010). The level of processing of the T2 stimuli is likely impeded when it is presented within the AB interval (short lag) and when task demand is high (T1-report), leading to low perceptual awareness. Consequently, the magnitude of attention shift to the target is diminished. Although this may contradict the view that attention is independent from and necessary for visual awareness (Cohen et al., 2012), the discrepancies between our conclusion and certain reports in the literature may be partly explained by the differences in the type of attention under examination. Our current findings highlight that spatial attention shifts (the N2pc) depend on perceptual awareness. It is possible, however, that other aspects of attention (e.g., scope of attention, feature-based attention; Koivisto et al., 2009) interact differently with awareness. Future studies could thus aim to examine the neural markers of other forms of attention and compare their relationship with perceptual awareness (the VAN) during the processing of emotional faces.

4.2. P3

Consistent with previous literature, we found a reduced P3 (400–700 ms) when visual awareness was restricted due to high task demands (i.e., T1-report), compared to when it was unrestricted (i.e., T1-ignore). The P3 component has been considered as a neural marker of reflective awareness and is suggested to increase in amplitude for consciously perceived information compared to information that fails to reach consciousness (Dehaene, 2014). Similar to our finding, previous AB studies have found that the P3 was reduced or absent when participants failed to detect the T2s, compared to when they consciously reported them (Fell et al., 2002; Kanske et al., 2013; Kranczioch et al., 2003; Sergent et al., 2005). However, how well the P3 reflects visual awareness *per se* is debatable. Recent research has argued against the idea that the P3 is a true neural correlate of awareness (Cohen et al., 2020; Dembski et al., 2021; Förster et al., 2020). Rather, the P3 has been found to be associated with a variety of higher-order cognitive processes including report-related processes (Koivisto and Revonsuo, 2010; Schupp et al., 2006) and information encoding in working memory (Busch and Herrmann, 2003; Morgan et al., 2008; Studer et al., 2010). Specifically, decreases in P3 amplitudes have been consistently associated with increases in working memory load across different paradigms (McEvoy et al., 1998; Mecklinger et al., 1992; Wijers et al., 1989; Zhou and Thomas, 2015). Our current finding could thus also be explained by the limited working memory available for T2 in the T1-report condition. Specifically, we found that the P3 was reduced for T2 appearing after an attended T1 with a short lag (hence inducing high working memory load), compared to when they disregarded the T1. In our study, it is likely that, when a T2 immediately followed an attended T1 (inducing an AB), the ongoing processing of T1 limited the available working memory for T2 (Taatgen et al., 2009). Consequently, a short-lag T2 was poorly encoded into working memory when T1 was attended, compared to when it was ignored. Of note, the effect of task type was not found in the long lag condition. It is likely that when T1 and T2 were separated by a long lag, sufficient processing of T1 had occurred to allow subsequent encoding of T2 in working memory.

4.3. SPCN

A later component was observed in our study which was larger for targets presented in the contralateral, compared to ipsilateral visual field. This appeared in the form of a sustained negative wave starting at around 400 ms at posterior brain regions, and was identified as the SPCN, the neural marker of the consolidation of perceptual information in working memory (for a review see Luria et al., 2016). In our study, the SPCNs were only found in the long lag condition and not in the short lag condition, suggesting that the consolidation of T2 was likely suppressed by the processing of T1 when the two targets were situated in close temporal proximity. Indeed, several previous AB studies have found that the SPCN was suppressed when T2 was presented within the AB interval of T1 (Dell'Acqua et al., 2006; Jolicœur et al., 2006a, 2006b). To the best of our knowledge, there has been no reports on the SPCN for fearful faces in AB. Extending on previous work (e.g., Dell'Acqua et al., 2006; Jolicœur et al., 2006a, 2006b, 2008), our results provide evidence that a target fearful face can elicit a strong SPCN in a bilateral AB paradigm and that the SPCN related to the fearful faces can be efficiently suppressed by interfering stimuli within close temporal proximity.

Additionally, we found that the SPCN positively correlated with the N2pc and the VAN, showing that working memory is affected by spatial attention and perceptual awareness. It is not surprising that, after spatial attention has been shifted to a target, the attended compared to unattended information can be better represented and maintained in working memory. The interactions between working memory and spatial attention have been extensively researched and discussed elsewhere (for a review see Oberauer, 2019; see also Awh and Jonides, 2001; Howard et al., 2020; LaBar et al., 1999). However, investigations on the relationship between visual awareness and working memory consolidation are rather limited. Our current study provides data suggesting that the electrophysiological activity of these two processes covaries in response to rapid and successive presentation of information.

In conclusion, using a bilateral AB paradigm, the current study provides electrophysiological evidence that spatial attention shifting to fearful faces, as indexed by the N2pc, depends on early perceptual awareness. Our study also extends on previous research on AB by revealing a sustained posterior contralateral negativity for fearful faces.

Credit author statement

Zeguo Qiu: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Validation; Visualization; Writing – original draft; Writing – review & editing. **Stefanie I. Becker**: Supervision; Writing – review & editing. **Alan J. Pegna**: Resources; Software; Supervision; Writing – review & editing.

Funding

Zeguo Qiu was funded by a PhD scholarship from the University of Queensland, Australia.

Declarations of competing interest

None.

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