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Research Report

Spatial attention shifting to emotional faces is contingent on awareness and task relevancy

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ABSTRACT

The relationship between visual attention and visual awareness has long been hotly debated. There has been limited evidence on whether the neural marker of spatial attention precedes or succeeds that of visual awareness in the processing of emotional faces. The current study aims to investigate the temporal sequence between the electrophysiological signatures of visual awareness (the visual awareness negativity – VAN) and spatial attention (the N2pc), in contexts where emotional faces are task-relevant (Experiment 1) or task-irrelevant (Experiment 2). Fifty-six healthy participants were presented with fearful and neutral faces under different levels of visibility using backward masking. They either performed a face detection task (Experiment 1) or a contrast detection task while ignoring the faces (Experiment 2). Compared to subliminal stimuli, supraliminal stimuli produced more negative ERPs at 170–270 msec and 210–310 msec in Experiments 1 and 2, respectively, identified as the VAN. The P3, a component also frequently considered to reflect awareness, produced a similar effect with larger amplitudes for supraliminal than subliminal stimuli in both experiments. With respect to spatial attention, a significant N2pc was observed in response to fearful faces but only in the supraliminal viewing condition of Experiment 1, in which faces were task-relevant. Crucially, the VAN was found to precede the N2pc in this case. Our results suggest that spatial attention as indexed by the N2pc, is oriented towards fearful faces when they are relevant to participants' task and are consciously processed. Moreover, an early phenomenal stage of awareness, reflected by the VAN, precedes spatial attention shifting to fearful faces.

1. Introduction

The relationship between visual awareness and visual attention has long been a key research interest. The extant literature has provided many investigations into the question using a variety of methodologies including behavioural and brain-based measurements. With conflicting findings in the literature, there have been two prominent views about the relationship between visual awareness and visual attention.

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One view holds that attention and awareness are two dissociable processes (for reviews see Koch & Tsuchiya, 2007; Tsuchiya & Koch, 2016), while the other suggests that they cannot be fully dissociated. In particular, attention has been suggested to be a prerequisite of awareness (for reviews see Cohen et al., 2012; Marchetti, 2012). Electroencephalography, or EEG, is a powerful tool that can be used to identify the electrophysiological markers (event-related potentials; ERPs) of visual attention and awareness in the human brain.

One well-established ERP marker of visual attention is the N2-posterior-contralateral component (N2pc), which is considered as an indicator of spatial attention and manifests as a relative negativity appearing at about 200–300 msec post stimulus at posterior brain areas contralateral to the attended side (Eimer, 1998; Kiss et al., 2008; Luck & Hillyard, 1994).

For visual awareness, the P3, a positive-going waveform appearing between 300 and 600 msec, was found to be enhanced in response to consciously processed (supraliminal) information relative to information that fails to reach conscious awareness (subliminal information; Dehaene, 2014). However, an earlier electrophysiological component identified more recently at around 200 msec post stimulus, appears to be linked to awareness and is termed the visual awareness negativity or the VAN (Förster et al., 2020; Koivisto & Revonsuo, 2003; Wilenius-Emet et al., 2004). This component manifests as a negative wave at posterior brain regions which emerges for supraliminal relative to subliminal stimuli.

Observations of the VAN and its correlation with visual awareness have been consistently reported across studies using different experimental paradigms including masking, binocular rivalry and inattention tasks (for reviews see Förster et al., 2020; Koivisto & Revonsuo, 2010). It has been suggested that the VAN and the P3 may reflect respectively early and late stages of visual awareness. Specifically, with an onset of around 200 msec, the VAN has been proposed to result from recurrent processing that occurs at posterior brain areas (Lamme, 2010). As the recurrent processing becomes more widespread across the cortex, information can then reach a higher level of awareness, which may be indexed by the P3, which is often maximal over parietal cortices (Cohen et al., 2020; Koivisto et al., 2018). In line with this distinction, previous research has specified different stages of awareness by distinguishing *phenomenal awareness*, a transient experience of perceptual information, likely reflected by the VAN, from *reflective awareness* that is characterised by post-perceptual processing, likely reflected by the P3 (e.g., Block, 1996; Cohen et al., 2020; Lamme, 2003).

The interactions between emotion processing and the attention system (Compton, 2003; Schupp et al., 2006; Yiend, 2010) or the awareness system (Niedenthal & Wood, 2019; Pessoa et al., 2005) have also been extensively studied. Emotional faces have been found to attract spatial attention more readily relative to neutral faces and ERP studies using face stimuli have frequently reported an N2pc for emotional faces (e.g., Holmes et al., 2009), even when the faces were irrelevant to the experimental tasks (Bar-Haim et al., 2005; Eimer & Kiss, 2007). For example, in a study by Eimer and Kiss (2007), participants were required to detect a luminance change of a central fixation point while ignoring arrays of face images. An N2pc was found for a fearful face among neutral faces even though participants' attention was directed to the central fixation point, away from the regions where the fearful face appeared. These results were taken to show that task-irrelevant emotional faces could elicit spatial attention shifts (Eimer & Kiss, 2007). However, research on the interactions between emotional relevance and task-relevancy has produced mixed results. Indeed, while some studies showed no effects of emotion on early ERPs (e.g., N170) when faces were task-irrelevant, others reported effects of task-relevancy on the early ERP signals (for a review see Schindler & Bublatzky, 2020). Notwithstanding, there has been very limited evidence of how task-relevancy of emotional faces may affect the N2pc using systematic investigations.

Emotional faces are not only prioritised from an attentional standpoint, but also compete for awareness. Indeed, modulations of emotional faces on early ERP components have been observed not only for supraliminally presented faces but also for subliminally presented ones (e.g., Del Zotto & Pegna, 2015; Kiss & Eimer, 2008; Pegna et al., 2008; Pegna et al., 2011). It has been suggested that the unconscious processing of emotional faces is reflected in the enhancement of the N170, a face-sensitive neural marker (Pegna et al., 2008). For example, Del Zotto and Pegna (2015) used centrally presented human faces of different emotions (e.g., fearful, angry, happy) and asked participants to respond to a specific emotion category. It was found that fearful faces elicited a larger N170 than happy and neutral faces, even when the stimuli were rendered subliminal using masking (Del Zotto & Pegna, 2015). They additionally found that the indicator of visual awareness (i.e., the VAN) succeeded the N170. It was therefore concluded that fearful faces can be processed in the absence of visual awareness (Del Zotto & Pegna, 2015). This rapid processing of subliminal emotional faces has been suggested to be enabled through a subcortical system that bypasses the visual cortex (Compton, 2003) and delivers coarse visual information to the amygdala (LeDoux, 2000; Tamietto & De Gelder, 2010). However, it is currently unclear whether subliminal emotional faces can elicit shifts of spatial attention and thus an N2pc. Indeed, as emotional faces are processed nonconsciously, subliminal presentations would likely elicit spatial attention shifts.

Therefore, it remains an open question how visual awareness and spatial attention interact, particularly where emotional faces are concerned, and whether task-relevance affects this interaction. The current study therefore aimed to investigate the relationship between spatial attention and awareness using faces, in situations where the emotions were either explicitly attended (Experiment 1) or not (Experiment 2). We used a bilateral presentation of human faces displaying fearful and neutral expressions under different levels of visibility. Participants' brain electrical activity were recorded using EEG to allow the electrophysiological markers of early face processing (N170), visual awareness (the VAN and the P3) and spatial attention shifting (the N2pc) to be examined. Specifically, we aimed to determine the temporal relationship between the VAN and the N2pc, and potential modulating effects of emotion on our components of interest (i.e., N170, VAN, P3 and N2pc).

We predicted that, if spatial attention shifts depend on phenomenal awareness, the VAN should precede the N2pc, and the N2pc to the fearful faces should only occur in supraliminal conditions. However, if phenomenal awareness depends on spatial attention shifts, the VAN should occur after the N2pc. Finally, if spatial attention shifts are independent of phenomenal awareness, the N2pc should occur regardless of stimulus visibility. Any nonconscious processing of emotional expression was expected to manifest as an enhancement of the N170 by fearful expressions, regardless of task goals.

2. Materials and method

We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

2.1. *Participants*

Forty-two and 29 participants with normal or corrected-to-normal vision at the University of Queensland were recruited for Experiment 1 and 2, respectively, and were compensated with either course credits or $30 (AUD) for their participation. Participants had no history of neurological or psychiatric conditions. Due to not providing sufficient data, 12 participants[1] and three participants[2] were excluded from Experiment 1 and 2, respectively (see ERP recording and pre-processing). As a result, the final sample included data from 30 participants ($M_{age} = 21.1$ years, $SD_{age} = 5.51$ years; 12 males, 18 females; 27 right-handed) for Experiment 1 and data from 26 participants ($M_{age} = 25.5$ years, $SD_{age} = 6.21$ years; 8 males, 18 females; all right-handed) for Experiment 2. The sample sizes were adequate for the repeated-measures ANOVAs we conducted because a sample size of 10 was necessary to obtain power of 90% and a large effect size of .4 (Cohen, 1988) at an alpha level of .05, two tailed (calculated with G*Power Software; Faul et al., 2009). 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 (refresh rate: 144 Hz; resolution: 1920 × 1080 pixels) placed 70 cm away from the participant's head. A Dell MOCZUL mouse and a Dell KB522p keyboard were wired to the monitor for participants to record responses. We used PsychoPy3 (Peirce et al., 2019) to present stimuli and record participants' behavioural data.

The face stimuli used in this experiment were obtained from the Karolinska Directed Emotional Faces Database (Goeleven et al., 2008). We selected the fearful face and neutral face images from 16 face identities (8 males, 8 females), thus in total 32 face stimuli. We cropped the face images into an oval shape of 8 cm × 6.2 cm (6.5° × 5.1° in visual angle) in order to keep only the facial information of each image (see Fig. 1a). Images were rendered black-and-white. The Scramble Filter tool (Telegraphics, 2021) was used on neutral faces to generate masks, which consisted of 208 squares (4.4 mm × 4.4 mm each) that were randomly scrambled to ensure the face was not identifiable while maintaining the same overall luminance (see scrambled faces in Fig. 1b). All the image editing was done in Photoshop 2021. For each face (or mask) presentation, two face (or mask) stimuli from a same face identity were presented bilaterally with the centre of the faces (or masks) positioned 5 cm (4.1° in visual angle) away from a central fixation cross on the screen. There were three combinations of face stimuli: a) fearful face on the left and neutral face on the right (Fearful Left); b) neutral face on the left and fearful face on the right (Fearful Right); c) two neutral faces (control). All stimuli were presented on a black screen.

For Experiment 2, the luminance of each face image was increased by 11% for one half of the image and was decreased by 11% for the other half. The contrast between the two halves created a line that was tilted either 52.2° or 127.8° away from the horizontal plane. Either the top or bottom part of the images was darker than the other half. Two lines on each face pair could either be tilted in the same direction (see Fig. 1c and d) or different directions (see Fig. 1e and f), and the participants' task was to report whether the lines were tilted in the same or different directions.

2.3. *Procedure*

As shown in Fig. 2, each trial started with a fixation screen of a variable duration between 500 and 800 msec, which was followed by a pair of faces that could be one of the three combinations mentioned above. The faces were presented for either 16 (subliminal) or 266 msec (supraliminal). Immediately after the face presentation, a pair of masks appeared for either 324 or 74 msec, so that the total duration of the face and mask stimuli was 340 msec for all trials. Then, after another fixation screen of 550 msec following the masks, participants were asked to respond. In Experiment 1, participants had to respond with one of the three mouse buttons to report on which side the fearful face had appeared (left mouse button = *appeared left*, right mouse button = *appeared right*, middle mouse button = *no fearful face*). In Experiment 2, participants responded with one of the two mouse buttons to indicate whether the lines on the faces were tilted in the same or different directions (left mouse button = *same*, right mouse button = *different*; 50% each). Directly afterwards, in both experiments, participants used the mouse to report the confidence level of their response to the first question on a four-point rating scale (1 = *Not confident at all*, 2 = *Not confident*, 3 = *Confident*, 4 = *Absolutely confident*). A blank screen of 500 msec was presented before the next trial began.

Participants were instructed to fixate at the screen centre unless they needed to move their eyes during the confidence rating. They were instructed to respond as accurately as possible after the question cue appeared on the screen. There were eight blocks of 72 trials with each of the three face combinations presented 192 times in total. Participants were allowed short breaks between blocks.

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[1] Results of the main analyses revealed the same effects when including all participants except one ($N = 41$) due to extremely limited useable epochs for this participant.

[2] Results of the main analyses revealed the same effects when all participants were included ($N = 29$).

(a) No lines; Fearful Left (b) Masks in both experiments

(c) Lines Same; Fearful Left (d) Lines Same; Control

(e) Lines Different; Fearful Left (f) Lines Different; Control

Fig. 1 – Examples of the face presentation in Experiment 1 (e.g., Fearful Left; a), the mask presentation (b) in Experiment 1 and 2, face presentation with lines tilted in the same direction when the fearful face is present (e.g., Fearful Left; c) and in the control condition (d), and face presentations with lines tilted in different directions (e and f).

2.4. *ERP 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 location. 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 a combination of BrainVision Analyzer 2.0 (BrainVision Analyzer 2.0, Brain products GmbH), EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014). We interpolated individual electrodes that produced either flatline signals or sustained noise throughout the experiment. Signals were re-sampled to 512 Hz offline, filtered from .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. ERP signals were segmented into epochs with a time window of 600 msec from the onset of the faces, relative to a pre-stimulus baseline (−100 to 0 msec). Trials with artefacts of eye blinks and eye movements were semiautomatically 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 12 participants were excluded for further analyses in Experiment 1 and data from three participants were excluded in Experiment 2 due to limited number of epochs remaining (i.e., fewer than 72 trials for each condition). On average 91% and 86% of the epochs were respectively kept for the remaining participants in Experiment 1 and 2.

2.5. *Data analysis*

2.5.1. *Behavioural data*

Because the participants were instructed to respond only after they saw the question prompt, we did not analyse their reaction time data. By contrast, accuracy and confidence ratings were analysed.

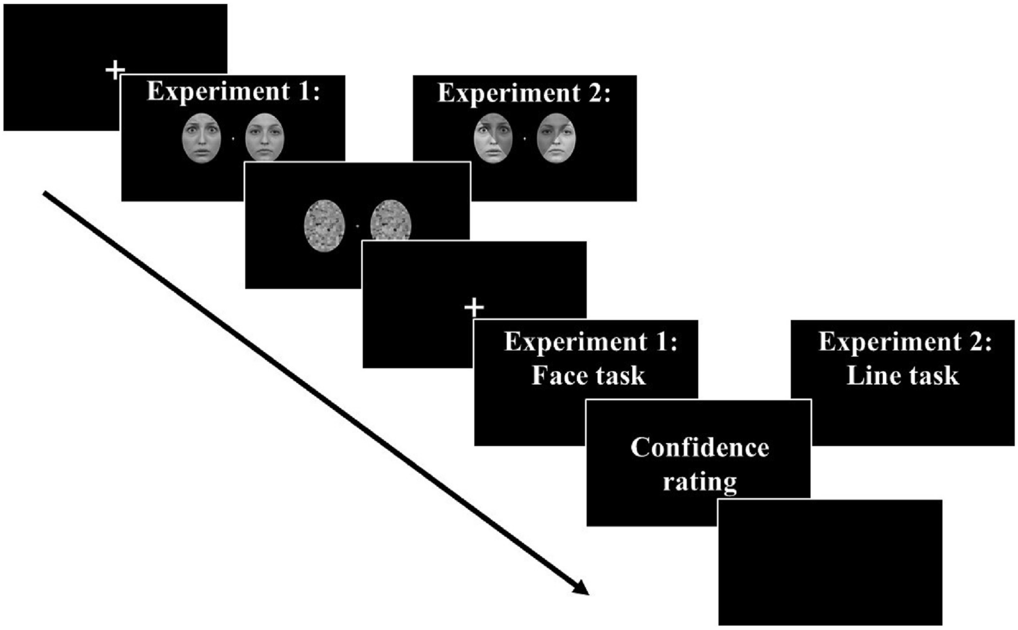


Fig. 2 – Time-course of events during a trial of the full experimental procedure for Experiment 1 and 2.

2.5.2. *ERP amplitudes*

In order to identify the electrodes and time windows that showed a significant difference between the supraliminal and subliminal conditions, we performed a Mass Univariate Analysis over all electrodes and time-points (0–600 msec post-stimulus) for significant differences (two-tailed family-wise $\alpha = .05$) 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/Mass_Univariate_ERP_Toolbox). Electrodes were considered as spatial neighbours if they were within approximately 3.9 cm of one another (‘chan_hood’ = 41 in this study), resulting in each electrode with on average 3.7 spatial neighbours (Groppe et al., 2011), and the cluster formation threshold was set at .05. We then pooled data from the identified electrodes and exported the mean amplitudes from these electrodes at the time windows that showed a significant effect of stimulus visibility. Topographic maps for subliminal and supraliminal conditions at the VAN and P3 time windows were plotted in Fig. 3.

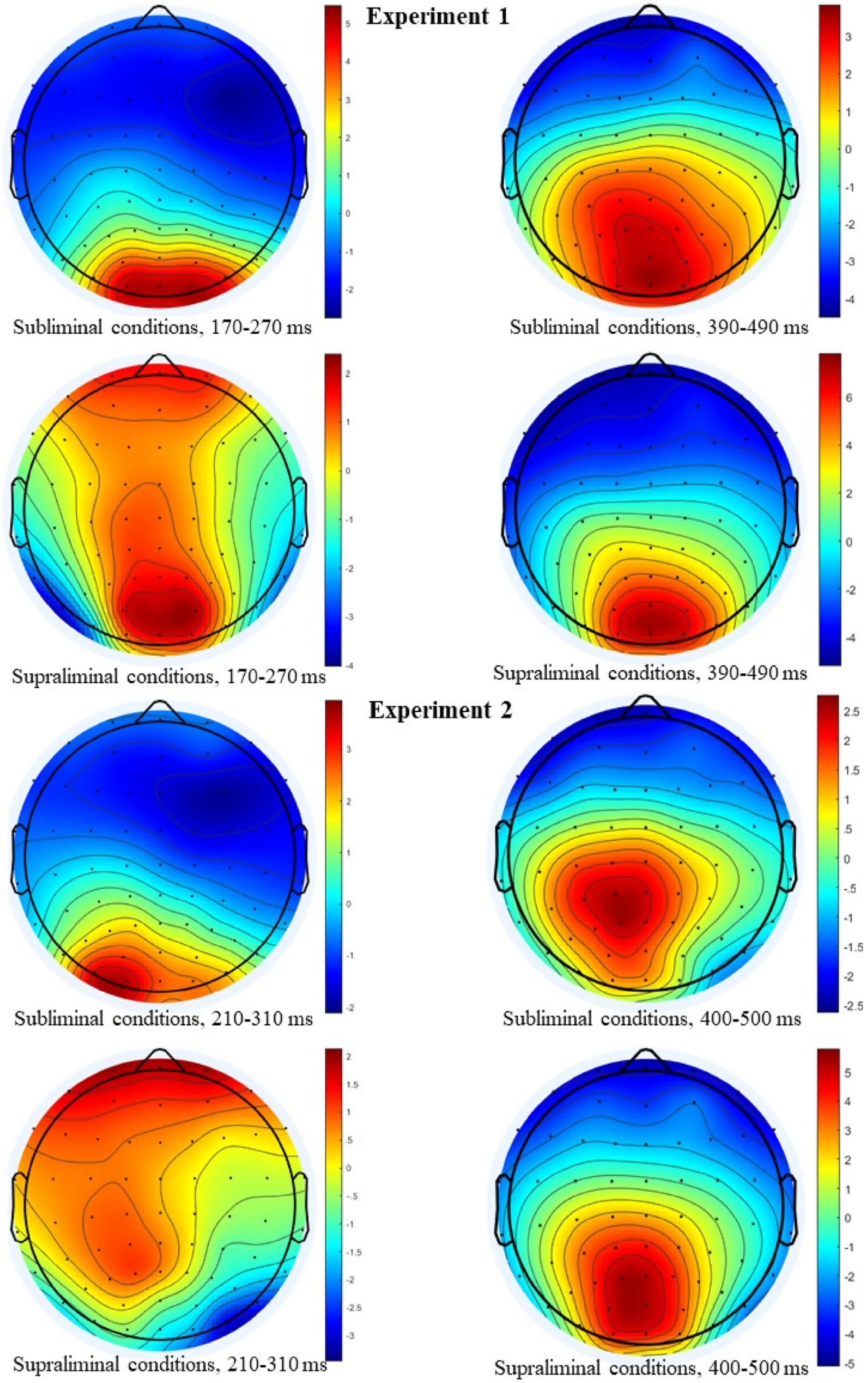
VAN. In Experiment 1, a significant effect of stimulus visibility was found on electrodes TP7/8, P3/4, P5/6, P7/8, P9/10, O1/2, PO3/4, PO7/8 in a common time window of 170–270 msec, reflecting a negative cluster. In Experiment 2, a significant effect of stimulus visibility was found on electrodes P3/4, P5/6, P7/8, P9/10, O1/2, PO3/4, PO7/8 in a common time window of 210–310 msec, reflecting a negative cluster. The analyses were all based on the mean amplitudes from these electrodes, separated by side (left, right).

P3. Following the same procedure as above, a significant effect of stimulus visibility was found on electrodes Pz, POz, Oz, P1/2, P3/4, PO3/4, O1/2 in a common time window of 390–490 msec, reflecting a positive cluster, in Experiment 1. In Experiment 2, a significant effect of stimulus visibility was found on electrodes CPz, Pz, POz, Oz, CP1/2, P1/2, P3/4, PO3/4 in a common time window of 400–500 msec, reflecting a positive cluster. We thus pooled data from these electrodes and exported the mean amplitudes of the specified time windows.

In an additional analysis, we separated the ERP data based on participants’ task performance (i.e., accuracy) for the VAN and the P3 time windows to investigate whether task performance correlates with awareness-related components (i.e., the VAN and the P3). Specifically, mean amplitudes were calculated separately for response-correct trials and response-incorrect trials. We had also planned to investigate the effect of different confidence levels on ERP results but this was not possible due to insufficient number of epochs at one or more levels of confidence ratings.

N2pc. An N2pc would manifest as an effect of laterality (a negativity towards contralateral 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 further 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.

N170. As we used human faces as stimuli, we additionally investigated the face-specific N170. Similar to the procedure described above, we performed a Mass Univariate Analysis to locate electrodes that showed a significant N170, averaged across face combinations at the supraliminal level. As a result, we pooled and exported data from T7/8, TP7/8, P7/8 and P9/10 in a common time window of 130–200 msec for Experiment 1. For Experiment 2, we pooled and exported data from TP7/8, P7/8 and P9/10 in a common time window of 130–200 msec.



Subliminal conditions, 170-270 ms

Subliminal conditions, 390-490 ms

Supraliminal conditions, 170-270 ms

Supraliminal conditions, 390-490 ms

Subliminal conditions, 210-310 ms

Subliminal conditions, 400-500 ms

Supraliminal conditions, 210-310 ms

Supraliminal conditions, 400-500 ms

Fig. 3 – Topographic maps for subliminal and supraliminal conditions, collapsed across face combinations, in the VAN time windows (170–270 msec for Experiment 1 and 210–310 msec for Experiment 2) and the P3 time windows (390–490 msec for Experiment 1 and 400–500 msec for Experiment 2).

2.5.3. ERP latencies

To examine the temporal sequence of the VAN and the N2pc, we analysed the onset latencies of the components. To obtain onset latency data, we used the fractional area latency algorithm (Kiesel et al., 2008; Lopez-Calderon & Luck, 2014). The onset latency of a component was defined as the time point when 20% of the area of the component has been reached (e.g., Lopez-Calderon & Luck, 2014).

All statistical analyses were performed in IBM SPSS Statistics 27. No part of the study procedures or analyses was preregistered prior to the research being conducted. The data and experimental materials for both experiments can be found on the Open Science Framework using the following link: https://osf.io/p4zks/

3. Results for Experiment 1: task-relevant faces (face task)

3.1. Behavioural results

3.1.1. Accuracy

Participants' accuracy in the task (fearful face location detection) was submitted to a 2(visibility: subliminal, supraliminal) X 3(face combination: Fearful Left, Fearful Right, control) repeated-measures ANOVA. Participants were significantly more accurate at the task when stimuli were supraliminal ($M = .87$, $SD = .11$) than when they were subliminal ($M = .36$, $SD = .04$; chance: .33), $F(1, 29) = 761.47$, $p < .001$, $\eta_p^2 = .96$. The effect of stimulus visibility was modulated by different face combinations, $F(2, 58)$[3] $= 15.25$, $p < .001$, $\eta_p^2 = .35$. Specifically, when stimuli were supraliminal, participants were significantly less accurate for the control trials ($M = .72$, $SD = .29$), compared to Fearful Left trials ($M = .93$, $SD = .12$), $t(29) = 3.46$, $p = .002$, $d = .63$, and Fearful Right trials ($M = .94$, $SD = .10$), $t(29) = 3.59$, $p = .001$, $d = .66$. However, for subliminal stimuli, participants were significantly more accurate for the control trials ($M = .53$, $SD = .31$), compared to Fearful Left trials ($M = .26$, $SD = .20$), $t(29) = 2.96$, $p = .006$, $d = .54$, and Fearful Right trials ($M = .28$, $SD = .19$), $t(29) = 2.89$, $p = .007$, $d = .53$. While the accuracy in subliminal conditions was significantly above chance for the control trials where no fearful face was present, $t(29) = 3.59$, $p = .001$, $d = .66$, the accuracy in fearful face-present trials was not different from chance performance (i.e., .33), $t(29) = 1.79$, $p = .083$, $d = .33$, for Fearful Left, $t(29) = 1.46$, $p = .156$, $d = .27$, for Fearful Right. Participants' task performance was not significantly different between the two fearful face present conditions at supraliminal level, $t < 1$, $p = .581$, or at subliminal level, $t < 1$, $p = .638$.

A more detailed analysis of behavioural responses revealed that participants were biased to give a "no fearful face" response in subliminal trials, and a "fearful face present" response in supraliminal trials. An analysis on the frequency of button pressing showed that, for all face combinations, participants were significantly more likely to press the middle button ("no fearful face") when stimuli were subliminal than the left button, $ts > 2.74$, $ps < .010$, $ds > .50$, and the right button, $ts > 2.57$, $ps < .015$, $ds > .47$ (fearful face on the left or right, respectively). For supraliminal stimuli, participants were more likely to press the correct button corresponding to where the fearful face had actually appeared, compared with the other two buttons ($ts > 20.34$, $ps < .001$, $ds > 3.71$, for Fearful Left trials; $ts > 23.40$, $ps < .001$, $ds > 4.27$, for Fearful Right trials). In control supraliminal trials, participants more frequently pressed the middle button to indicate no fearful face had appeared, compared with the left and right buttons, $ts > 6.20$, $ps < .001$, $ds > 3.13$. However, they seemed to also have a preference for the right button over the left, $t(29) = 2.40$, $p = .023$, $d = .44$, in control trials.

In addition, participants were less likely to press the correct middle button for control supraliminal trials, compared with responding correctly for Fearful Left trials, $t(29) = 3.46$, $p = .002$, $d = .63$, and for Fearful Right trials, $t(29) = 3.59$, $p = .001$, $d = .66$. These results indicate that participants were reluctant to provide a "no fearful face" response for control supraliminal trials, leading to a lower accuracy compared with the fearful face present conditions. In contrast, for subliminal trials, the higher accuracy for control trials was likely driven by an overall tendency to press the middle button over the other two options.

3.1.2. Confidence rating

To additionally examine the relationship between the two dependent variables (accuracy and confidence ratings), and test whether stimulus visibility and/or the presence of a fearful face affects this relationship, we ran a Linear Mixed-effects Model analysis on all available datapoints using the restricted maximum likelihood method to estimate model parameters and Satterthwaite approximations for the degrees of freedom (Luke, 2017). First, we recoded the face combination variable into a new variable; Fearful Presence (0 = *Fearful Absent*, 1 = *Fearful Present*). Then, we entered stimulus visibility, Fearful Presence and accuracy as fixed factors into the model. To account for between-participant variance, we included participant as a random factor (West, 2009). Results showed that stimulus visibility was a significant predictor of confidence, $F(1, 24{,}001) = 7398.99$, $p < .001$. Compared to subliminal stimuli, supraliminal stimuli were associated with higher confidence ratings overall, $\beta = 1.70$, $SE = .02$, $p < .001$. Fearful Presence ($F(1, 24{,}001) = 115.24$, $p < .001$) and accuracy ($F(1, 24{,}002) = 1081.55$, $p < .001$) were also significant predictors of confidence ratings. Specifically, participants were more likely to have higher confidence ratings when they were correct at the task, $\beta = .82$, $SE = .03$, $p < .001$, and when there was a fearful face in the visual display, $\beta = .32$, $SE = .01$, $p < .001$.

Importantly, the positive relationship between accuracy and confidence ratings was modulated by stimulus visibility and Fearful Presence, which was demonstrated by a significant three-way interaction, $F(1, 24{,}014) = 59.00$, $p < .001$. We followed this interaction up by running Linear Mixed-effects Models separately for supraliminal and subliminal conditions, including Fearful Presence and accuracy as two fixed factors and participant as a random factor. Results showed that, for supraliminal stimuli, both variables significantly predicted confidence ratings, $Fs > 421.19$, $ps < .001$.

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[3] Greenhouse-Geisser correction was used because the assumption of sphericity was violated. Uncorrected degrees of freedom are reported here. The Greenhouse-Geisser epsilon is .547.

Specifically, participants had higher confidence ratings when a fearful face was present, $\beta = .34$, $SE = .01$, $p < .001$, and when they were correct at the task, $\beta = .67$, $SE = .03$, $p < .001$. Fearful Presence did not interact with accuracy on predicting confidence ratings, $F(1, 15{,}529) = 1.79$, $p = .181$. For subliminal stimuli, overall, neither variables could predict confidence ratings, $Fs < 3$, $ps > .083$. However, we found a significant interaction between the predictors, $F(1, 8474) = 12.29$, $p < .001$, reflecting a significant effect of accuracy on predicting confidence ratings when a fearful face was present, $F(1, 5643) = 12.41$, $p < .001$, but not when it was absent, $F(1, 2817) = 2.55$, $p = .110$. It seems that for subliminal stimuli, participants had higher confidence ratings when they were correct at the task only for the Fearful face present condition, though the effect was very small, $\beta = .07$, $SE = .02$, $p < .001$.

3.2. *ERP results*

3.2.1. *VAN and N2pc time window*

To examine the neural correlate of phenomenal awareness, we exported the mean amplitudes over the waveforms in the VAN time window (170–270 msec) for the following analyses. Because a preliminary check showed that electrode site did not interact with stimulus visibility or laterality, we pooled the left and right electrodes together and ran a 2(visibility: subliminal, supraliminal) X 3(laterality: contralateral, ipsilateral, control) repeated-measures ANOVA. The amplitudes were significantly more negative for supraliminal stimuli ($M = -.81$ μV, $SD = 2.36$ μV) than subliminal stimuli ($M = 2.14$ μV, $SD = 2.16$ μV), $F(1, 29) = 239.03$, $p < .001$, $\eta_p^2 = .89$ (see Fig. 4a and b; VAN difference waves are plotted in Fig. 4c and d). We also found a main effect of laterality, $F(2, 58) = 9.40$, $p < .001$, $\eta_p^2 = .25$, which was modulated by an interaction with stimulus visibility, $F(2, 58)$[4] $= 4.08$, $p = .032$, $\eta_p^2 = .12$. Follow-up paired-sample t-tests showed that, for supraliminal stimuli, negative deflections contralateral to the fearful face ($M = -1.09$ μV, $SD = 2.43$ μV) were significantly larger than those ipsilateral to the fearful face ($M = -.57$ μV, $SD = 2.38$ μV), $t(29) = 4.52$, $p < .001$, $d = .83$, and those in the control[5] condition ($M = -.76$ μV, $SD = 2.35$ μV), $t(29) = 3.09$, $p = .004$, $d = .56$. No effect of laterality was found for subliminal stimuli, $F < 1$, $p = .436$. These results show that, compared to subliminal stimuli, supraliminal emotional faces likely underwent a deeper processing in this time window, especially at brain regions contralateral to the emotional face, indicating a significant N2pc in the supraliminal viewing condition, see Fig. 5.

We further calculated the N2pc difference waves by subtracting signals ipsilateral to the target fearful face from those contralateral to the target fearful face. For the N2pc amplitudes at subliminal level, a Bayesian one-sample t-test provided anecdotal evidence for the null hypothesis ($BF_{01} = 2.04$). These results show that the N2pc, an indicator of spatial attention shifting, was only observed for supraliminal stimuli.

To examine whether accuracy at the task correlates with the VAN, the data of the VAN (supraliminal minus subliminal) amplitudes were divided into task-correct (mean trial number $= 317$, $SD = 94$) and task-incorrect groups (mean trial number $= 200$, $SD = 88$). Participants with no ERP data in one or more sub-conditions were excluded for this analysis. As a result, only 15 participants were included for a 2(accuracy) X 3(laterality) repeated measures ANOVA on the VAN amplitudes. Results showed that the main effect of accuracy was non-significant, $F < 1$, $p = .501$. Accuracy also did not interact with laterality, $F < 1.88$, $p = .172$. Therefore, it seems that task performance was not associated with changes in the VAN amplitudes.

We obtained similar results after excluding data from the control condition.

3.2.2. *VAN and N2pc latencies*

By using the fractional area latency technique, we obtained onset latencies of the VAN and the N2pc waveforms. To cover the maximal spans of the ERP components, a common time window of 150–400 msec was selected for the VAN and the N2pc.

A paired-sample t-test on data from 29 participants[6] showed that the onset of the VAN ($M = 195$ msec, $SD = 15$ msec) was significantly earlier than the onset of the N2pc ($M = 224$ msec, $SD = 27$ msec), $t(28) = 5.55$, $p < .001$, $d = 1.03$.

3.2.3. *P3 time window*

To examine the neural correlate of reflective awareness, we ran a 2(visibility: subliminal, supraliminal) X 3(face combination: Fearful Left, Fearful Right, control) repeated-measures ANOVA on the mean P3 amplitudes (390–490 msec). We found a main effect of stimulus visibility with a significantly more positive P3 for supraliminal stimuli ($M = 5.44$ μV, $SD = 3.15$ μV) than subliminal ones ($M = 2.99$ μV, $SD = 2.22$ μV), $F(1, 29) = 55.10$, $p < .001$, $\eta_p^2 = .66$ (see Fig. 4e and f). A main effect of face combination was also revealed, $F(2, 58) = 20.63$, $p < .001$, $\eta_p^2 = .42$, which was modulated by an interaction with stimulus visibility, $F(2, 58) = 12.65$, $p < .001$, $\eta_p^2 = .30$. Follow-up paired-sample t-tests showed that, at the supraliminal level, compared to the control condition where no fearful face was present ($M = 4.74$ μV, $SD = 3.34$ μV), the P3 was significantly larger for Fearful Left trials ($M = 5.87$ μV, $SD = 2.99$ μV), $t(29) = 6.29$, $p < .001$, $d = 1.15$, and for Fearful Right trials ($M = 5.71$ μV, $SD = 3.24$ μV), $t(29) = 6.27$, $p < .001$, $d = 1.14$. Fearful Left and Fearful Right trials did not significantly differ from each other, $t < 1$, $p = .350$. Face combination did not affect the P3 amplitudes for subliminal stimuli, $F < 1$, $p = .441$. These results show that the faces enhanced the electrical activity when presented supraliminally relative to subliminal presentations, especially for displays that involve an emotional face.

Furthermore, we performed a 2(accuracy) X 3(face combination) repeated measures ANOVA on the amplitudes of the accuracy-dependent P3 difference waves (supraliminal minus

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[4] Greenhouse-Geisser correction was used because the assumption of sphericity was violated. Uncorrected degrees of freedom are reported here. The Greenhouse-Geisser epsilon is .784.

[5] For control trials, amplitudes were averaged across the left and right electrode sites. Negative deflections ipsilateral to supraliminal fearful face were not significantly different from supraliminal control condition, $t(29) = 1.87$, $p = .071$.

[6] One participant did not show a clear N2pc peak.

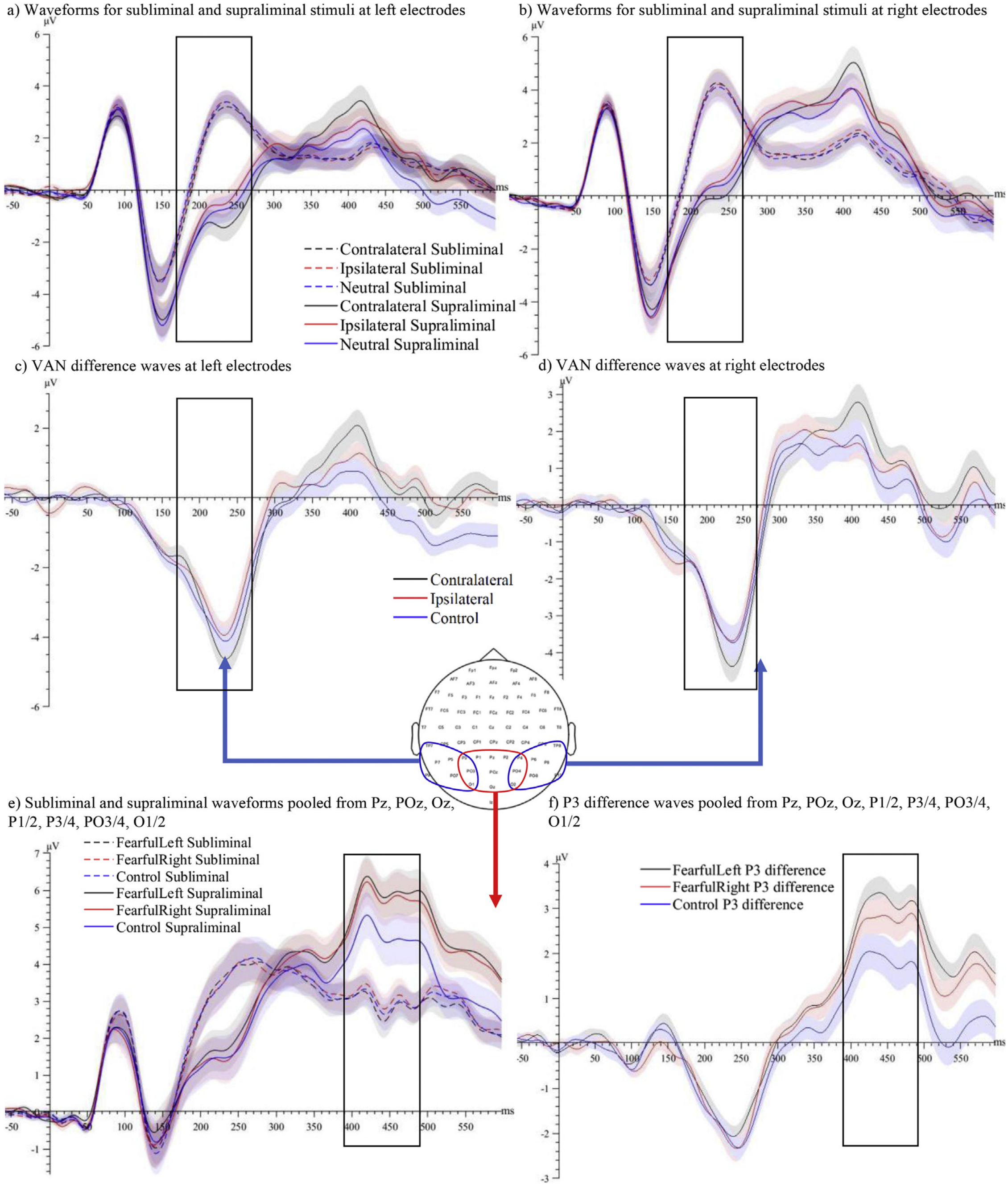

Fig. 4 – Waveforms of contralateral, ipsilateral and control conditions at left (pooled from TP7, P3, P5, P7, P9, O1, PO3, PO7; a) and right electrodes (pooled from TP8, P4, P6, P8, P10, O2, PO4, PO8; b). VAN difference waves (supraliminal waves minus subliminal waves) for contralateral, ipsilateral and control conditions at left (c) and right electrodes (d). P3 (e) and P3 difference waves (f; supraliminal waves minus subliminal waves) for different face combinations pooled from Pz, POz, Oz, P1/2, P3/4, PO3/4, O1/2. The shaded areas show the significant time windows of the components.

subliminal). The main effect of accuracy was marginally significant, $F(1, 14) = 4.40$, $p = .055$, $\eta_p^2 = .24$, reflecting that the P3 difference waves was slightly larger for correct trials ($M = 2.78$ μV, $SD = 1.62$ μV) than incorrect trials ($M = 1.76$ μV, $SD = 1.91$ μV). These results show that being correct than incorrect at the task was associated with enhanced neural activity in the P3 time window. No other effect was significant, $Fs < 1.80$, $ps > .185$.

3.2.4. *N170 time window*

To examine the neural correlate of early face processing, a 2(visibility: subliminal, supraliminal) X 3(face combination: Fearful Left, Fearful Right, control) repeated-measures ANOVA was performed on the mean amplitudes from the N170 time window (130–200 msec), collapsed across hemisphere. We found a main effect of stimulus visibility, $F(1, 29) = 177.89$, $p < .001$, $\eta_p^2 = .86$, with supraliminal stimuli eliciting

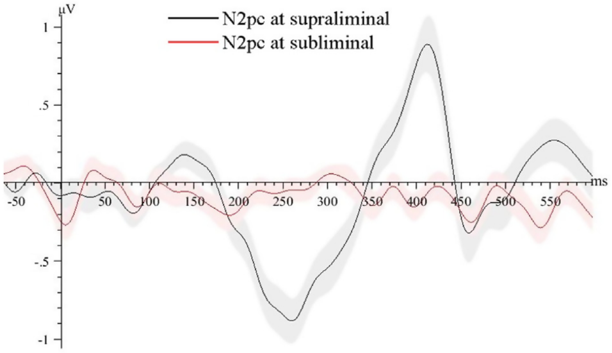

Fig. 5 – The N2pc difference waves for subliminal and supraliminal conditions.

significantly more negative signals ($M = -4.73$ µV, $SD = 2.26$ µV) than subliminal stimuli ($M = -2.81$ µV, $SD = 1.88$ µV). No other effect was significant, $Fs < 1$, $ps > .444$.

To summarise, Experiment 1 revealed a negative ERP with an onset of ~195 msec for supraliminal stimuli compared to subliminal stimuli, identified as a VAN. A P3 at 390–490 msec was also found to be larger in supraliminal than subliminal viewing conditions. Furthermore, emotion interacted with both the VAN and the P3. The presence of a target stimulus in either visual half field produced a significant N2pc with an onset of ~224 msec only in supraliminal conditions, indicating spatial attention shifts. Importantly, the onset of the VAN was significantly earlier than that of the N2pc. Additionally, the N170 was larger in supraliminal relative to subliminal conditions but it was not modulated by emotion.

To investigate whether task-relevancy of the faces affects the above-described effects, we conducted a second experiment where the overall design remained the same but the faces were made irrelevant to participants' task.

4. Results for Experiment 2: task-irrelevant faces (line task)

4.1. *Behavioural results*

Participants' accuracy in the lines judgement task was submitted to a 2(visibility: subliminal, supraliminal) X 3(face combination: Fearful Left, Fearful Right, control) X 2(lines direction: same, different) repeated-measures ANOVA. Participants were significantly more accurate at the task when stimuli were supraliminal ($M = .91$, $SD = .10$) than when they were subliminal ($M = .50$, $SD = .03$), $F(1, 25) = 415.09$, $p < .001$, $\eta_p^2 = .94$, where accuracy was at chance performance (.5). No other main effect or interaction was significant, $Fs < 3.31$, $ps > .081$.

Additionally, to examine the relationship between the two dependent variables (accuracy and confidence ratings), we ran a Linear Mixed-effects Model analysis on all available datapoints. Same as in Experiment 1, face combination was recoded into a new variable Fearful Presence (0 = *Fearful Absent*, 1 = *Fearful Present*). Stimulus visibility, Fearful Presence and accuracy were entered into the Linear Mixed-effects Model as fixed factors. Participant was entered as a random factor to control for between-participant variance. Results showed that both stimulus visibility ($F(1, 17{,}099) = 6413.30$, $p < .001$) and accuracy ($F(1, 17{,}101) = 566.60$, $p < .001$) were significant predictors of confidence ratings. Specifically, compared to subliminal stimuli, supraliminal stimuli were associated with higher confidence ratings overall, $\beta = 1.52$, $SE = .01$, $p < .001$. Participants were also more likely to have higher confidence ratings when they were correct at the task, $\beta = .67$, $SE = .03$, $p < .001$. However, as suggested by a significant interaction between stimulus visibility and accuracy, $F(1, 17{,}101) = 567.37$, $p < .001$, the effect of accuracy ($\beta = .50$, $SE = .02$, $p < .001$) on predicting confidence ratings was only significant for supraliminal stimuli, $F(1, 8528) = 648.76$, $p < .001$, and not for subliminal stimuli, $F < 1$, $p = .354$. No other effect was significant, $Fs < 1.05$, $ps > .305$.

4.2. *ERP results*

4.2.1. *VAN time window*

To examine the neural correlate of phenomenal awareness, we analysed the mean amplitudes over the waveforms in the VAN time window (210–310 msec). A preliminary check showed that the left and right electrodes did not interact with stimulus visibility or laterality. Thus, we pooled the data over the left and right electrodes and ran a 2(visibility: subliminal, supraliminal) X 3(laterality: contralateral to a fearful face, ipsilateral to a fearful face, control) repeated-measures ANOVA. The ERP amplitudes were significantly more negative for supraliminal stimuli ($M = -1.30$ µV, $SD = 3.43$ µV) than subliminal stimuli ($M = 1.77$ µV, $SD = 3.06$ µV), $F(1, 25) = 127.41$, $p < .001$, $\eta_p^2 = .84$ (see Fig. 6a and b; see the VAN difference waves in Fig. 6c and d). No other effect reached significance, $Fs < 1$, $ps > .375$. These results suggest that supraliminal stimuli were associated with stronger electrical activity at this stage, compared to subliminal stimuli, and this effect was not modulated by the emotional expression of the faces.

To examine the relationship between task accuracy and the VAN, the data of the VAN (supraliminal minus subliminal) amplitudes were divided into task-correct (mean trial number = 337, $SD = 39$) and task-incorrect (mean trial number = 155, $SD = 36$) groups. Participants with no ERP data in one or more sub-conditions were excluded for this analysis. As a result, data from 17 participants were included for a 2(accuracy) X 3(laterality) repeated measures ANOVA on the VAN amplitudes. No main effect of accuracy was found, $F < 1.29$, $p = .272$, showing that task performance was not associated with changes in the VAN amplitudes. All other effects were non-significant, $Fs < 1.09$, $ps > .327$.

As shown in Fig. 7, we did not identify any differences between the ERP waves contralateral and ipsilateral to a fearful face in the conventional N2pc time window (i.e., 200–300 msec), showing that participants did not shift their spatial attention to the fearful face.

4.2.2. *P3 time window*

To examine the neural correlate of reflective awareness, we performed a 2(visibility: subliminal, supraliminal) X 3(face combination: Fearful Left, Fearful Right, control) repeated-measures ANOVA on the mean P3 amplitudes (400–500 msec). We found a significantly more positive P3 for

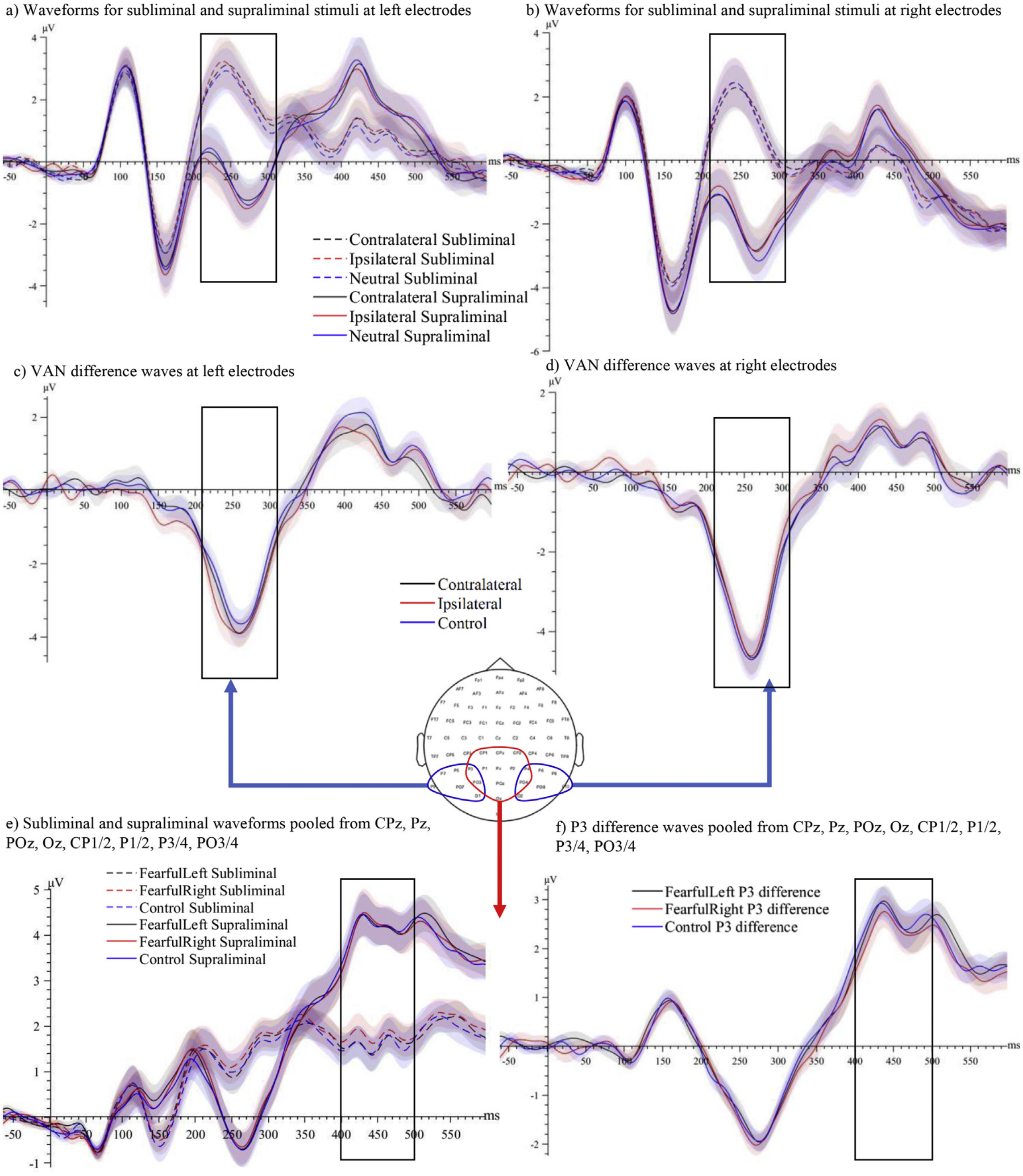

Fig. 6 – Waveforms of contralateral, ipsilateral and control conditions at left (pooled from P3, P5, P7, P9, O1, PO3, PO7; a) and right electrodes (pooled from P4, P6, P8, P10, O2, PO4, PO8; b). VAN difference waves (supraliminal waves minus subliminal waves) for contralateral, ipsilateral and control conditions at left (c) and right electrodes (d). P3 (e) and P3 difference waves (f; supraliminal waves minus subliminal waves) for different face combinations pooled from CPz, Pz, POz, Oz, CP1/2, P1/2, P3/4, PO3/4. The shaded areas show the significant time windows of the components.

supraliminal stimuli (M = 4.12 μV, SD = 2.04 μV) relative to subliminal ones (M = 1.65 μV, SD = 1.68 μV), $F(1, 25) = 77.33$, $p < .001$, $\eta_p^2 = .76$ (see Fig. 6e and f). No other effect was significant, $Fs < 1$, $ps > .404$. These results show that, relative to subliminal stimuli, supraliminal stimuli enhanced the electrical activity in this time window, regardless of the emotional expression of the faces.

We additionally performed a 2(accuracy) X 3(face combination) repeated measures ANOVA on the amplitudes of the P3 difference waves (supraliminal minus subliminal) dependent on task accuracy. Only data from 17 participants were included for this analysis. The main effect of accuracy was significant, $F(1, 16) = 4.97$, $p = .040$, $\eta_p^2 = .24$, reflecting a larger P3 difference for correct trials (M = 2.77 μV, SD = 1.70 μV) than incorrect trials (M = 1.89 μV, SD = 2.12 μV). No other effect was significant, $Fs < 1$, $ps > .827$. The results indicate that being correct than incorrect at the task elicited a stronger neural processing in the P3 time window.

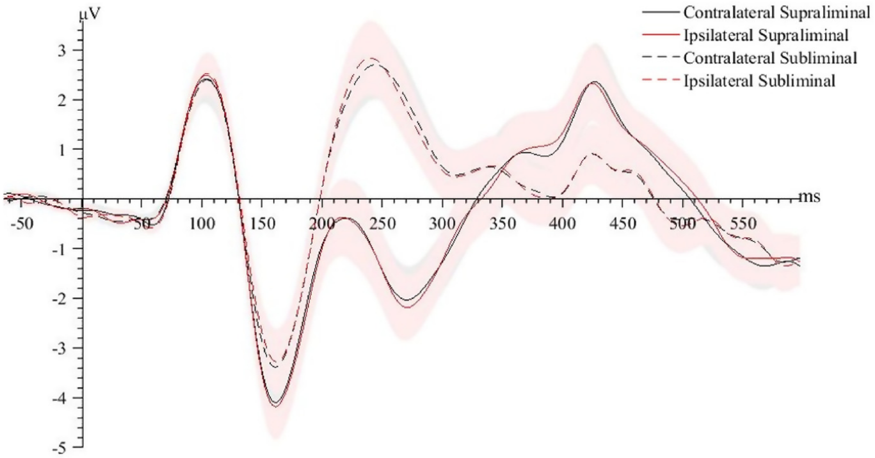

Fig. 7 – The ERP waves of contralateral and ipsilateral signals to the fearful face for subliminal and supraliminal conditions, pooled from P3/4, P5/6, P7/8, P9/10, O1/2, PO3/4, PO7/8.

4.2.3. *N170 time window*

To investigate the neural correlate of early face processing, a 2(visibility: subliminal, supraliminal) X 3(face combination: Fearful Left, Fearful Right, control) repeated-measures ANOVA was performed on the mean amplitudes from the N170 time window (130–200 msec), collapsed across hemisphere. The main effect of stimulus visibility was significant, $F(1, 25) = 79.07$, $p < .001$, $\eta_p^2 = .76$, with supraliminal stimuli eliciting significantly more negative signals ($M = -4.82$ μV, $SD = 2.84$ μV) than subliminal stimuli ($M = -3.20$ μV, $SD = 2.49$ μV). No other effect was significant, $Fs < 1$, $ps > .467$.

To summarise, in Experiment 2 where the faces were task-irrelevant, visual information presented supraliminally elicited a more negative ERP (210–310 msec), compared to the same information presented subliminally, identified as a VAN. We also found a larger P3 (400–500 msec) and a larger N170 for supraliminal stimuli than subliminal ones. No N2pc was found towards the irrelevant fearful faces and emotion did not modulate the N170, the VAN or the P3.

5. Discussion

In the current study, two experiments were carried out in which fearful and neutral faces were presented bilaterally above or below the threshold of visibility while participants were asked either to detect the fearful expressions (Experiment 1), or to ignore the emotional expressions while responding to variation in luminance on the stimuli (Experiment 2).

The neural correlates of awareness (the VAN and the P3) were found in both experiments. The electrophysiological signature of spatial attention shifting, the N2pc, was only found in the supraliminal viewing condition of Experiment 1 and appeared after the VAN. Modulating effects of emotional expressions on the VAN and the P3 were observed, again only in Experiment 1. Additionally, in both experiments, the face-sensitive N170 was modulated by stimulus visibility but not by emotion.

5.1. *Neural correlates of visual awareness*

In both experiments, we found that supraliminal stimuli were associated with a more negative ERP signal than subliminal stimuli at posterior electrode sites in the time range between 200 and 300 msec, which was identified as a VAN. As mentioned in the Introduction, the VAN has been proposed as an early electrophysiological marker of visual awareness (Förster et al., 2020; Koivisto & Revonsuo, 2010) and is often observed in the occipito-temporal regions in the human brain (Förster et al., 2020). The VAN manifests as a negative deflection in response to visible stimuli, as opposed to stimuli that are rendered invisible either by masking or inattention. With an onset of ~200 msec post stimulus, the VAN has been suggested to reflect phenomenal awareness (Eklund & Wiens, 2018), likely reflecting the early conscious processing of visual information (Block, 1996; Lamme, 2003). For example, in a study using low-contrast Gabor patches (Koivisto & Grassini, 2016), large amplitude differences at around 200 msec post stimulus (the VAN) at posterior brain areas were found between correct trials with and without reported awareness. By controlling for the potential confound of performance, they showed that the VAN was indeed a neural correlate of phenomenal awareness, the experience of conscious percept (Koivisto & Grassini, 2016). Post-perceptual processes such as response selection, likely occur after this and thus cannot influence the VAN. Consistent with this and with previous observations (e.g., Eklund & Wiens, 2018; Koivisto & Grassini, 2016), we found that the VAN did not correlate with task performance in either Experiment 1 or Experiment 2.

We also found that the P3 was enhanced for supraliminal relative to subliminal stimuli in both experiments. This component has been proposed as a likely indicator of the reflective process of awareness (Förster et al., 2020). Some researchers have argued that the P3 does not reflect awareness *per se* but other related cognitive processes like the evaluative appraisal of the stimuli (Pitts et al., 2014), task-driven top-down attention (for a review see Polich, 2007) or decision making (for a review see Railo et al., 2011). For example, the P3 was found to vary with non-awareness related processes (e.g., task-relevancy of the stimuli and participants' confidence levels; Pitts et al., 2014; Polich, 2007) in addition to awareness, or found not to correlate with awareness at all when participants' attention scope was restricted (Koivisto et al., 2006). In both our experiments, we found a larger P3 difference for correct responses relative to incorrect ones, though this effect reached statistical significance only in Experiment 2. This appears to support the idea that the P3 is indeed sensitive to post-perceptual processes such as task performance. However, our analysis in this case was carried out on data from small subgroups of participants (15 out of 30 participants in Experiment 1 and 17 out of 26 participants in Experiment 2), limiting the interpretability of these observations.

The N170 was also enhanced in response to supraliminal faces, compared to subliminal ones in both experiments. This finding is in line with previous studies showing that the early stage of face processing can be modulated by stimulus visibility (De Pascalis et al., 2020; Navajas et al., 2013; Sandberg et al., 2013), but at odds with those reporting comparable N170 amplitudes for unconsciously and consciously-processed faces (e.g., Harris et al., 2013; Suzuki & Noguchi, 2013). These discrepancies may lie in the paradigms used to disrupt awareness. Indeed, in studies using inattention (e.g., Harris et al., 2013) or continuous flash suppression (e.g., Suzuki & Noguchi, 2013), neural responses to unaware stimuli at the visual cortices are suggested to be delayed or weakened, while in backward masking paradigms, subliminal face processing is disrupted during the early processing stages, likely interrupting recurrent processing in the primary visual cortices (Enns & Di Lollo, 2000). Consequently, the early stages of neural activity, although sensitive to face stimuli, are much weaker in this case, possibly explaining the reduced N170 in the present study.

5.2. *Spatial attention shifting is contingent on visual awareness*

More importantly for our research question, we identified different onset latencies for neural markers of phenomenal awareness (VAN) and spatial attention shifting (N2pc) in Experiment 1, showing that the VAN emerged prior to the N2pc. To the best of our knowledge, our study is the first to tease apart the VAN and the N2pc temporally in the processing of emotional faces. The temporal sequence between these two neural correlates has so far remained unexplored. As a result, previous research on the relationship between phenomenal awareness and spatial attention may not have insights on how the two processes unfold over time. Here, we provide clear evidence that phenomenal awareness indexed by the VAN appears prior to spatial attention shifting that is indexed by the N2pc.

Crucially, we also found that the N2pc was dependent on stimulus visibility. Specifically, in Experiment 1, the shift of spatial attention towards the target face in bilateral presentations occurred only when the faces were consciously perceived by the participants. This is consistent with studies using the change blindness paradigm where the N2pc was found when the changes were consciously identified or localised (Busch et al., 2010; Howe & Webb, 2014; Scrivener et al., 2019), compared to change-blind situations. Comparable results have also been found in studies using object-substitution masking (Crouzet et al., 2017) and a motion detection paradigm (Boncompte & Cosmelli, 2018).

The absence of the N2pc in response to stimuli that failed to reach awareness is consistent with the claim that the way spatial attention operates is changed in the absence of awareness (Webb et al., 2016). According to these authors, while attention shifting is possible without awareness, it is less stable across the visual fields (Webb et al., 2016; see also; Derda et al., 2019). Specifically, using metacontrast masking to manipulate participants' awareness of a visual cue, they showed that when the visual cue was presented subliminally, the efficiency of attention shifting towards a subsequent target at the same location fluctuated substantially as the cue-target time interval increased. In comparison, when participants were consciously aware of the cue, they could shift their attention equally efficiently across varied time intervals to the subsequent target because their attention was engaged on the cue and was thus more stable (Webb et al., 2016). These observations could also apply to our current results. In our paradigm, when the stimuli appeared subliminally, participants' attention may not have efficiently engaged the target face due to the less stable shift that ensued, resulting in the absence of an N2pc and chance-level performances in detecting the location of the target face.

The question that emerges is thus how to reconcile previous reports of spatial attention capture by subliminal emotional faces with our current findings indicating the precedence of awareness over attention shifting. Indeed, some behavioural studies have reported results suggesting attentional capture by masked facial expressions (e.g., Carlson & Reinke, 2008; Fox, 2002; Mogg & Bradley, 1999), although this view is not undisputed (e.g., Milders et al., 2008; Pessoa et al., 2005). One possible cause for this is that masking studies may not have used parameters that entirely preclude conscious detection. For instance, in a behavioural study where stimulus durations were varied systematically, Pessoa et al. (2005) found that the threshold of detection varied across participants, and that durations of presentation of 33 msec, which are frequently used, are in fact above the threshold of awareness for a number of participants. From an electrophysiological perspective, few studies have specifically examined the interaction between emotion, awareness, and spatial attention. Carlson and Reinke (2010) examined the early ERP response to lateralised subliminal fearful faces. Their results revealed an enhanced lateralised N170 for fearful faces presented in the right visual field. This was taken as evidence of attentional capture by subliminal fearful faces, particularly as the ERP findings correlated with behavioural performance. However, this study did not specifically examine the electrophysiological markers of visual awareness, nor of spatial attention shifting. Moreover, the durations of presentation used in this study (i.e., 33 msec; Carlson & Reinke, 2010) may have been sufficient to allow conscious processing, possibly accounting for the some of these results.

Our current findings therefore indicate that, despite the biological relevance and the task-relevancy of the fearful face, if visual awareness (as indexed by the VAN) does not emerge, spatial attention (as indexed by the N2c) does not occur. One alternate explanation remains possible however, namely that the N2pc only reflects a conscious form of spatial attention shifting, while alternate networks might produce unconscious attention shifts. This idea was proposed by Giattino et al. (2018) to explain the absence of an N2pc in their study. These authors presented a face or house image as a cue for 17 msec, prior to a target square. The subliminally-presented cue was found to elicit an N2pc only when the participants reported awareness of the cue, but not when they were unaware of it (Giattino et al., 2018). However, the authors observed an enhanced processing of the subliminally-cued target both at the behavioural level (faster reaction times for the target following the unseen cue) and at the electrophysiological level (enhanced P1 for the cued target). It was thus concluded that attention shifting had occurred despite the absence of awareness of the cues (Giattino et al., 2018). In order to account for this apparent incompatibility, the authors suggested that the effects on attention might have resulted from neural activity that differed from that indexed by the N2pc in particular (Giattino et al., 2018). Our experiment does not allow us to conclude regarding this possibility and further experiments are necessary to verify this possibility.

Since the results of our study point to awareness occurring prior to spatial attention shifting, a model such as that of recurrent processing seems to provide a useful explanation. According to the recurrent processing framework (Lamme, 2003), visual information must go through a multi-level process (i.e., feedforward and feedback processes) before it can reach phenomenal awareness and, dependent on the depth of processing, attract spatial attention (Lamme, 2003, 2010). However, when briefly presented (e.g., 16 msec) and backward masked, recurrent processing, necessary to visual awareness, is impeded (Lamme, 2003, 2010).

Effects of emotional expression were also noted on the components associated with awareness. In Experiment 1, enhanced responses were produced by the fearful expression, again only in supraliminal viewing condition. Specifically, the mean amplitudes of the VAN time window contralateral to the fearful face were more negative than those ipsilateral to the fearful face in supraliminal viewing condition (i.e., N2pc towards the fearful target face). The P3 in supraliminal but not subliminal conditions was also enhanced by the fearful expression. Fearful expressions could be processed with priority because they are intrinsically important for our survival as they are often associated with potential threats in the environment (Öhman & Mineka, 2001). The modulating effects of supraliminally presented emotion on the VAN and the P3 are consistent with the literature where an enhancement of awareness-related components was found during the elaborate processing of a fearful face, compared to other emotions (e.g., Balconi & Mazza, 2009; Sokolov & Boucsein, 2000; Williams et al., 2006). By contrast, we did not observe any modulating effect of emotion on awareness-related ERP signals in subliminal viewing condition. The absence of emotion effects in subliminal conditions is seemingly in contradiction to previous studies that found evidence for the rapid processing of emotional faces without conscious awareness (e.g., Del Zotto & Pegna, 2015; Framorando et al., 2021; Pegna et al., 2008; Pegna et al., 2011). For example, emotional faces including fearful faces have been found to modulate the N170 in subliminal viewings, before the emergence of the VAN (Del Zotto & Pegna, 2015; Pegna et al., 2008). Although we did not observe any enhancement on the N170 by the fearful expression in either experiment, this finding is in line with previous studies that reported a lack of emotion-modulating effect on the N170 in paradigms where bilateral faces were also presented (Eimer et al., 2003; Framorando et al., 2018; Holmes et al., 2003; Pourtois et al., 2004). One possible explanation for these inconsistencies is that, perhaps, during the early neural processing in the N170 time window, the two lateralised faces strongly competed for neural representation, preventing any modulating effect of face emotion from emerging at this stage. In our case, emotion did not modulate the N170 even when the emotional face was also the target stimulus (Experiment 1). Therefore, it seems that the early ERP response to emotional information (i.e., the N170) presented peripherally may be highly restricted, if not completely absent, when it is in competition with similarly salient information (e.g., another face) on the opposite side.

Taken together, it seems that the neural processing of laterally presented fearful faces was not sufficient to modulate early neural activity (N170), or to affect the neural correlates of awareness (the VAN and the P3) and spatial attention shifting (N2pc) when the faces were presented subliminally.

5.3. *Conscious spatial attention shifting is contingent on task-relevancy*

Interestingly, in Experiment 2 where the faces were irrelevant to the task, we did not find an N2pc in either supraliminal or subliminal viewing conditions. That is, in Experiment 2, fearful faces presented laterally did not elicit spatial attention shifts, even when stimuli were consciously processed by the participants. This is in agreement with studies suggesting that attentional capture by emotional faces is not automatic but context-specific (e.g., affected by attentional control; Barratt & Bundesen, 2012; Zhou et al., 2020; or by target competition; Wirth & Wentura, 2018). In our Experiment 2, the saliency of the fearful expression may have been suppressed to allow more efficient processing of task-relevant information (i.e., lines). Supporting this, we did not find any modulating effect of emotion on the VAN or the P3 in Experiment 2 in either supraliminal or subliminal conditions. That is, the presence of a task-irrelevant fearful face in the display did not influence either awareness-related component. While participants' attention was drawn to the regions where the faces were presented, they were instructed to attend to face-irrelevant information, the tilted lines imposed onto the faces. Perhaps, the task of attending to the lines and making an accurate representation of them inhibited further processing of competing information such as the emotion of the faces. Consequently, fearful faces could not elicit a spatial attention shift (i.e., an N2pc) and did not modulate visual awareness of the stimuli (i.e., the VAN and the P3).

More recent research has found that active suppression of task-irrelevant stimuli is possible, even when the stimuli are very salient (e.g., colour singletons; Gaspelin et al., 2017; Gaspelin & Luck, 2018a, 2018b). Evidence for top-down suppression mechanisms on salient yet task-irrelevant stimuli have been documented in ERP studies (Gaspar & McDonald, 2014; Kiss et al., 2012; Liu et al., 2020; Mertes et al., 2016; Sawaki & Luck, 2010), including studies using task-irrelevant emotional faces (Eimer et al., 2003; Rellecke et al., 2012; Yang et al., 2015). For example, in a study by Eimer et al. (2003) using bilateral presentations of human faces of different emotions, modulating effects of emotion were observed on ERP correlates in all examined time windows (from 120 to 700 msec post stimulus), but only when the faces were task-relevant. The emotion effects on the ERPs completely disappeared when the same face stimuli became task-irrelevant (Eimer et al., 2003). While participants in the study of Eimer et al. (2003) were required to attend to the central regions, away from the bilaterally presented faces in face-irrelevant conditions, in our study, participants' attention was directed to the same spatial areas of the faces. Therefore, our study provides new evidence for the top-down suppression of salient yet task-irrelevant information by showing that competing information (i.e., fearful faces) presented at overlapping spatial regions of the task-relevant stimuli could be efficiently suppressed from processing.

However, previous literature has also reported an automatic attentional capture by emotional faces (e.g., Elam et al., 2010; Fox, 2002; Koster et al., 2005). One hypothesis that has been put forward to account for the discrepant findings is the attentional load account (Lavie et al., 2004). Lavie and collaborators (e.g., Lavie, 2010; Lavie et al., 2004) have suggested that attentional capture occurs only when sufficient attentional resources are available. Previous fMRI research showed that, when attentional resources were available for supraliminal face stimuli, several brain regions including the amygdala showed stronger activation for emotional compared to neutral faces. However, when participants' attention was engaged in a task of high attentional load, brain activation did not differ across emotional and neutral expressions (Pessoa et al., 2002). In line with this, Lien et al. (2013) used ERP to study attention capture by fearful faces. The authors presented faces or coloured boxes as cues for upcoming target stimuli and examined the N2pc to the cue stimuli. They found that the N2pc to a fearful face cue was found only when the participants had to identify a fearful face in the target display. In this case, the face stimuli were task-relevant and matched the attentional control setting of the participants. However, in the face-irrelevant condition where participants identified letters in a coloured box, fearful face cues did not elicit an N2pc, showing that when attentional resources were tuned to non-face stimuli (i.e., coloured boxes and letters), the fearful expression did not capture attention.

In our study, we attempted to create a procedure where the orthogonal task did not involve the facial expressions, where the feature to be attended nevertheless coincided with the face stimuli. It could be argued that, in Experiment 2, participants' attentional resources were deployed on another task and the attentional load remained high enough, which prevented attentional capture by the fearful expressions even in the supraliminal viewing condition. Such an interpretation cannot be excluded here and future research would be required to address this aspect more specifically.

5.4. *Contributions of the current study and future directions*

The current study expands on the view that attention and awareness are distinct processes (e.g., Tsuchiya & Koch, 2016) by showing that spatial attention shifting is dissociable from, yet dependent upon phenomenal awareness. Crucially, the shifting of spatial attention that is associated with the N2pc occurred only for supraliminal task-relevant information, even though the information is salient and biologically-relevant (i.e., emotional faces). Although this may contradict some claims in the existing literature on the attention-awareness relationship, the discrepancies may be partly reconciled if the nature of attention being investigated is clearly defined and manipulated. Indeed, while the current findings provide clear evidence that the shift of spatial attention (the N2pc) depends on phenomenal awareness, other forms or aspects of attention (e.g., spatial attention locus, feature-based attention) may be associated with different neural mechanisms and may interact with awareness differently.

Furthermore, experimental paradigms and visual stimuli are also important factors to consider when examining the attention-awareness relationship. Paradigms other than backward masking have been widely used to manipulate visual awareness (for reviews see Förster et al., 2020; Hutchinson, 2019; Kiefer & Kammer, 2017; Pitcher et al., 2021). For example, the inattentional blindness has been frequently used in previous experiments, and results from these experiments seem to suggest consistently that attention is necessary for awareness. In a typical inattentional blindness study, participants often fail to notice a stimulus when their focal attention is engaged in a secondary task that incurs a high cognitive load and/or competes with task-relevant stimuli (Hutchinson, 2019; Mack, 2003). As a result, focal attention covaries with awareness in these experiments. Additionally, ERP differences in the VAN time window are rarely discussed in these inattention studies, limiting the scope of the investigations to the relationship between focal attention and the more reportable reflective awareness (e.g., Chica et al., 2010; Fernandez-Duque et al., 2003; Sommer et al., 1990). Future research could thus aim to examine the neural markers of other forms of attention and compare their relationship with both the VAN and the P3 across experimental paradigms.

To conclude, our current results provide electrophysiological evidence of the precedence of visual awareness over spatial attention shifting to emotional faces, and thus that awareness is necessary for subsequent attention shifting. This was demonstrated by the fact that spatial attention shifting, indexed by the N2pc, occurred only when the stimuli reached a sufficient level of awareness, indexed by the VAN. Importantly, the VAN emerged prior to the N2pc, and the N2pc was not present when the emotional expressions were not relevant to participants' task.

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**: Methodology; Supervision; Writing – review & editing. **Alan J. Pegna**: Conceptualization; Methodology; Resources; Software; Supervision; Writing – review & editing.

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Open practices

The study in this article earned Open Data, Open Materials and Preregistered badges for transparent practices. Materials and data for the study are available at https://osf.io/p4zks/.

Declaration of competing interest

None.

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