



# Pre-stimulus alpha predicts inattention blindness

Brendan T. Hutchinson<sup>\*</sup>, Kristen Pammer, Bradley Jack

Australian National University, Canberra, Australia

University of Newcastle, Newcastle, Australia

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## ABSTRACT

Pre- and post-stimulus oscillatory activity between 8 and 12 hertz, referred to as the alpha-band, correlates with conscious visual awareness of stimuli across a variety of psychophysical tasks. Within an EEG-adapted inattention blindness task, the current study sought to examine whether this relationship holds for conscious awareness of stimuli under conditions of inattention blindness. Noticing rates of the task-irrelevant unexpected stimulus were correlated with a significant decrease in alpha power over bilateral parietal-occipital areas during the pre-stimulus interval, and a significant decrease in alpha power over parietal-occipital regions in the right hemisphere during the post-stimulus interval. Findings are taken to imply alpha-band neural activity represents a valid correlate of consciousness that is not confounded by task relevancy or the need for report.

## 1. Pre-stimulus alpha predicts inattention blindness

Recent work on the neural basis of consciousness has uncovered several candidate brain signals associated with awareness—termed the neural correlates of consciousness (NCC's). These include electroencephalographic (EEG) signatures of both low (e.g. alpha, Iemi, Chaumon, Crouzet, & Busch, 2017; Ronconi & Bellacosa Marotti, 2017) and high (e.g. gamma, Panagiotaropoulos, Deco, Kapoor, & Logothetis, 2012) frequency activity, at pre- (van Dijk, Schoffelen, Oostenveld, & Jensen, 2008) and post- (Harris, Dux, & Mattingley, 2018) stimulus periods, and in both early visual (Romei, Gross, & Thut, 2010) and late frontal processing regions (Boly et al., 2017). The question now posed is which neural candidates are representative of the genuine mechanism responsible for consciousness (NCC-proper), as opposed to pre-requisite brain signals associated with anticipation and preparation (pre-NCC's), and post-perceptual brain signals associated with higher cognitive functions such as memory, decision making, and report (post-NCC's) (Aru, Bachmann, Singer, & Melloni, 2012; Tsuchiya, Wilke, Frassle, & Lamme, 2015).

### 1.1. Alpha: A genuine NCC?

Alpha-band refers to EEG activity in the frequency range between 8 and 12 Hz. Commonly observed within parietal-occipital regions, alpha is associated with visual perception across a variety of tasks. Unique from activity in other frequency bands, alpha negatively correlates with neural excitation, such that it increases when brain regions are less involved in sensory processing (Jensen, Bonnefond, & VanRullen, 2012; VanRullen & Dubois, 2011). This understanding has emerged from observations that a reduction in alpha correlates with various measures of neural excitation, including increases in gamma activity (Basar, Basar-Eroglu, Karakas, &

<sup>\*</sup> Corresponding author at: Research School of Psychology, Australian National University, Canberra, ACT 2612, Australia.

E-mail address: [Brendan.hutchinson@anu.edu.au](mailto:Brendan.hutchinson@anu.edu.au) (B.T. Hutchinson).

Schurmann, 2000) and blood oxygen level dependent activity, as measured via functional magnetic resonance imaging (Becker, Reinacher, Freyer, Villringer, & Ritter, 2011; Goldman, Stern, Engel, & Cohen, 2002). Once interpreted as cortical “idling”, there is an emerging view that alpha oscillations may have a functional role in the inhibition of task-irrelevant information (see the *inhibition timing* hypothesis, Klimesch, Sauseng, & Hanslmayr, 2007; the *p1 inhibition timing* hypothesis, Klimesch, 2011; the *knowledge system* hypothesis, Klimesch, 2012; the *gating by inhibition* hypothesis, Jensen & Mazaheri, 2010; the *pulsed inhibition* account, Mathewson et al., 2011; the *temporal phase coding* hypothesis, Jensen et al., 2012; Jensen, Gips, Bergmann, & Bonnefond, 2014; and the *cognitive control* hypothesis, Sadaghiani & Kleinschmidt, 2016).

Current theoretical views stem from research which has examined the relationship between 1) alpha and visual attention, and 2) alpha and visual consciousness. First, alpha is selectively modulated by shifts in attention (Kelly, Lalor, Reilly, & Foxe, 2006; Thut, Nietzel, Brandt, & Pascual-Leone, 2006; Worden, Foxe, Wang, & Simpson, 2000), such that when attention is manipulated, alpha responds in a predictable and retinotopically specific manner. A robust decrease in alpha is typically observed in the hemifield associated with the processing of attended or “relevant” stimuli (i.e. contralateral to the stimulus; Sauseng et al., 2005), while an increase in alpha occurs in the hemifield associated with the processing of unattended or “irrelevant” stimuli (Worden et al., 2000). Second, both amplitude and phase angle of alpha predict detection and discrimination of visual stimuli (Babiloni, Vecchio, Bultrini, Luca Romani, & Rossini, 2006, for review, see Iemi et al., 2017). A reduction in alpha prior to the presentation of a stimulus typically predicts whether it is perceived (Hanslmayr et al., 2007; Mathewson, Gratton, Fabiani, Beck, & Ro, 2009; Romei, Gross, & Thut, 2010; van Dijk et al., 2008), though increases in pre-stimulus alpha have also been shown to correlate with detection and psychophysical performance (Babiloni et al., 2006; Linkenkaer-Hansen, Nikulin, Palva, Ilmoniemi, & Palva, 2004; Mayer, Schwiedrzik, Wibral, Singer, & Melloni, 2016; Zhang, Wang, Bressler, Chen, & Ding, 2008). Similarly, a reduction in post-stimulus alpha following stimulus presentation has been observed for those stimuli that uniquely reach conscious awareness (Levy et al., 2013; Magazzini, Ruhnau, & Weisz, 2016; Harris et al., 2018).

Despite both spheres of research implying a close relation between alpha and consciousness, alpha’s role as an NCC is not often made explicit. Yet, as with other potential NCC’s, methodological issues limit the extent to which its putative role in consciousness can be differentiated from, for example, anticipatory mechanisms (e.g. pre-NCC’s). Similarly, the relationship between awareness and alpha activity in the absence of report has not yet been systematically examined (but see Kloosterman et al., 2015). As such, conclusions are limited as to what alpha’s precise role is in the chronology of conscious visual processing.

### 1.2. No report and inattentional blindness

To tease apart different stages of processing linked with conscious perception, researchers have recently adopted no-report paradigms. No-report paradigms offer a workaround to the issue of confounding neural signatures associated with conscious visual awareness with those associated with reporting on one’s awareness (Tsuchiya et al. 2015). In such tasks, participants are not required to report on what they are aware of; at least, not initially. This allows one to examine neural signatures associated with consciousness without undue influence of those processes needed to produce reports, such as memory, decision-making, or motor planning. Within a no-report inattentional blindness paradigm, recent work by Pitts et al. (2012, 2014) demonstrated that the p300, one of the most robust NCC’s, occurs only when participants are required to access and report on their percept. As per the no-report methodology, participants progressed through ten minutes of the experiment before they were queried on their awareness of the critical stimulus. This meant that the stimulus, which was unexpected and task-irrelevant, was presented hundreds of times without any report-related effect confounding their measurements.

The no-report methodology lends itself well to the neural study of inattentional blindness (IB). In brief, IB refers to the failure to perceive an unexpected visual stimulus when engaged in a separate demanding task (Jensen, Yao, Street, & Simons, 2011). In an experimental setting, IB provides a robust method for suppressing conscious awareness of a stimulus through manipulation of attention resources (Ward & Scholl, 2015). For example, participants may be instructed to perform a demanding task, such as counting the number of ball passes in a basketball game (Simons & Chabris, 1999). After a given length of time, something unexpected yet conspicuous occurs well within participants’ view—such as a gorilla parading through the basketball game—and when asked, participants often fail to report noticing it.

Whereas many trials are required to achieve an adequate signal-to-noise ratio when collecting neuroimaging data (e.g. EEG), IB studies can typically only include a single critical trial because prior knowledge about the critical stimulus abolishes the effect (but see Ward & Scholl, 2015). This was overcome by Pitts et al. (2012) through the development of a paradigm in which the critical stimulus was presented hundreds of times within the spatially attended region at well above threshold levels, but without explicit task instructions pertaining to its presence or relevancy. Instead of probing participants’ awareness of the critical stimulus immediately, they delayed the questioning until it was presented hundreds of times. For all participants, the critical stimulus was initially unexpected, and if it was perceived, it remained irrelevant during the first 10-minute block of the experiment. There was consequently no need to provide trial-by-trial reports on its visibility. Careful questioning afterward allowed for a block-wise classification of participants as either “aware” or “inattentionally blind” to the critical stimulus. The differences in neural signatures associated with the processing of the critical stimulus could then be contrasted between groups, presumably void of any report-related neural confounds.

### 1.3. The current study

The current study adapted the Pitts et al. (2012) paradigm to examine pre- and post-stimulus alpha activity under conditions of IB. A relative decrease in alpha is typically associated with both the locus of attention and visual awareness (Worden et al., 2000; Romei

et al., 2008). In line with this pattern, one would therefore expect a relative decrease in alpha to be associated with noticing the critical stimulus under conditions of IB. However, correlations between pre- (and post-) stimulus alpha and awareness are typically observed in studies where stimuli have remained task-relevant and thus require a response. This might suggest the relationship between alpha and visual awareness has been conflated by its role in attention (Sauseng et al., 2005), the gating of task-relevant processing (Jensen & Mazaheri, 2010), or other report-related confounds (Tsuchiya et al., 2015). The paradigm developed by Pitts et al. (2012) offers an advantage here, in that it facilitates a better understanding of the neural signatures associated with task-irrelevant visual awareness. Recent work by Harris et al. (2018) similarly used a lateralization-adapted version of the task developed by Pitts et al. (2012), and found a significant reduction in post-stimulus (300–700 ms) alpha activity correlated with awareness of the critical stimulus. However, they did not include the third phase of the task where the critical stimuli of which awareness was measured became task relevant. Here, we used the original variant of the paradigm, i.e. with non-lateralized stimuli and with the third phase of the task included. Our aim was to examine the relationship between both pre- and post- stimulus alpha and visual consciousness of unexpected and task-irrelevant stimuli.

## 2. Method

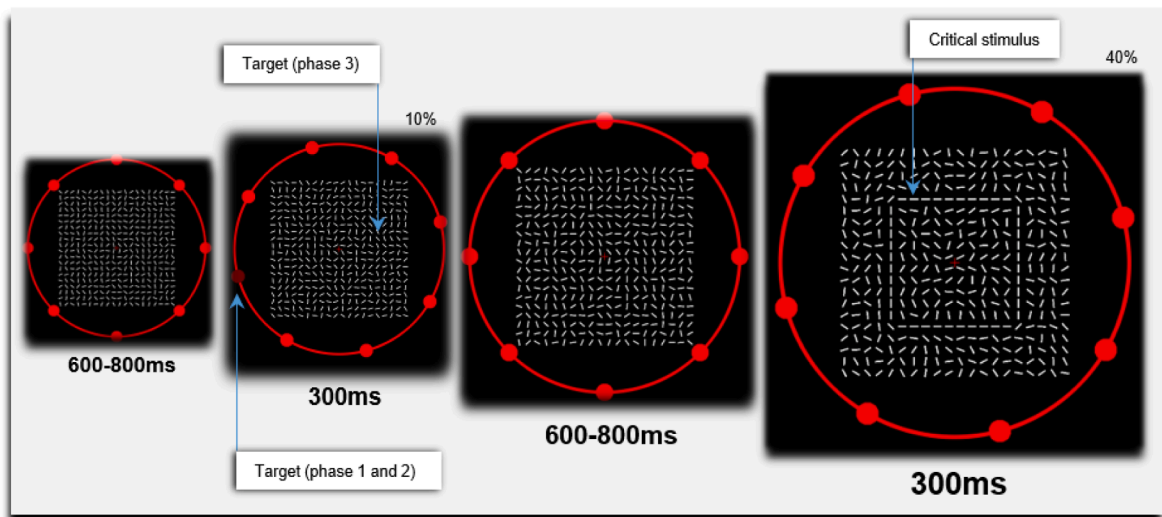
### 2.1. Participants

A total of 31 participants were recruited from the Australian National University. Data from six participants were later excluded due to either excessive EEG artefacts (i.e. outliers in artefact rejection) or technical issues arising during data collection. The final sample consisted of 25 participants ( $M$  age = 19.96,  $SD$  = 1.97, range = 18–25; 12 male, 13 female). All participants provided informed consent prior to participating and were remunerated with \$20 AUD. The experiment was approved by the university ethics committee (protocol number: 2017/262).

### 2.2. Stimuli and procedure

All stimuli were presented on a dark background ( $0.07 \text{ cd/m}^2$ ) on an LCD monitor with a refresh rate of 60 Hz using Psychopy software (Peirce, 2007). At a viewing distance of 57 cm, participants were presented with a central grid of 400 ( $20 \times 20$ ) line segments, each subtending approximately  $0.45^\circ$  visual angle. The line segments remained at a baseline static random configuration for 600–800 ms, and then formed one of three ‘stimuli’ for 300 ms: a square pattern (44 line segments, approx.  $7^\circ$  visual angle), a diamond pattern (28 line segments, approx.  $8 \times 6^\circ$  visual angle), or a random array (see Fig. 1). The line array grid was surrounded by a red ring of eight discs (each approx.  $1^\circ$  visual angle) that remained static for 600–800 ms and then rotated for 300 ms (concurrent with the line segment orientation changes) either clock wise or counter clockwise by  $15^\circ$  to form one of two alternate positions (see Fig. 1). On ten percent of the orientation changes, the luminance of one of the eight discs was decreased by 40% (the “target” for phase 1 and phase 2).

The square pattern represented the critical stimulus of which IB was measured and was presented on 40% of stimulus sequences (approx. 240 presentations per “phase”, i.e. ten trials). The diamond pattern was the target for phase 3 (see Fig. 1) and was presented on 10% of stimulus sequences (approx. 60 presentations per phase). On the other 50% of stimulus sequences, a new random



**Fig. 1.** Example Stimulus Sequence, *Note.* The target (the disc for phase 1 and 2; the diamond for phase 3) was presented on 10% of orientation changes for a duration of 300 ms and was interspersed by randomly oriented line arrays for 600–800 ms. Note that the diamond and disc were not always presented simultaneously and are together here for demonstration. The critical stimulus (i.e. the square) was presented on 40% of orientation changes, whilst the other 50% of orientation changes were composed of randomly oriented line arrays.

configuration was presented (approx. 300 presentations per phase). Thus, across the experiment, there was a total of approximately 1800 stimulus presentations (600 per phase).

Participants completed a total of 35 trials: five practice trials that preceded phase one, followed by 30 experimental trials. Each trial ran for approximately 60 s. During practice trials, no experimental stimuli were presented, rather the line segments always formed random arrays. Experimental trials were broken into three phases of ten trials. Across phase 1 and phase 2, participants were instructed to fixate on a cross ( $0.5^\circ$ ) presented at the centre of the line segment array and were to respond with a key response when they detected the target disc (i.e. decrease in luminance) that occurred on ten percent of the orientation changes. This task (the “distractor” task) was designed to tax participants’ visuospatial attention sufficiently to induce inattention blindness to the square array. In phase 3, participants were instead instructed to respond with a key response when they detected the diamond pattern within the line array grid. Practice trials consisted of the distractor task, therefore participants had no practice on the diamond detection task of phase 3. Self-paced breaks were taken after every trial, with mandatory extended breaks after every five trials.

Participants received a questionnaire regarding shapes within the line segments after the first phase. This served both as a measurement of IB, and to induce an expectation of the shape patterns. The questionnaire initially queried participants with a 2-alternative forced choice item (yes / no) whether they noticed any patterns within the line arrays, and an open-ended item which asked to describe what they saw. Following these, participants were presented with example images of stimuli and were asked to rate their confidence in having seen the stimuli during the experiment (1 = very confident I did not see it; 2 = confident I did not see it; 3 = uncertain; 4 = confident I saw it; 5 = very confident I saw it) and how frequently they had noticed it (1 = never; 2 = rarely / less than 10 times; 3 = infrequently / 10–50 times; 4 = frequently / 50–100 times; 5 = very frequently / more than 100 times). The same questionnaire was provided after phase 2 to ensure participants noticed the square array while performing the task.

### 2.3. EEG

Data were recorded at a sample rate of 1024 Hz (down-sampled to 256 Hz offline) using a 64-channel BioSemi Active Two system. Six additional external electrodes were applied for recording horizontal (outer canthi of each eye) and vertical eye (above and below the left eye) movements (both re-referenced offline to single bipolar horizontal and vertical channels), as well as the left and right mastoids. In place of conventional ground electrodes, the BioSemi system employs two separate passive electrodes, the “Common Mode Sense” and “Driven Right Leg”. These electrodes serve as an online “reference” through formation of a feedback loop, however data is stored reference free. Offline, data were re-referenced to the average of all scalp electrodes (Dien, 1998). Electrode impedance was kept below 5 k $\Omega$ . EEG-activity was time locked to the orientation change.

Data pre-processing and analyses were carried out using BESA 6.1 (MEGIS Software GmbH, Gräfelfing, Germany). To reduce slow drift and DC noise, data were high-pass filtered at 0.53 Hz using a forward roll-type filter with a slope of 6 dB per octave, and notch filtered at 50 Hz (2 Hz width, as per Australian standards). Data were then epoched into time windows of  $-600$  to  $+600$  ms relative to stimulus onset, with 2 s padding windows on either side of the epoch as per BESA’s time frequency module. Baseline normalization occurred from  $+300$  to  $+600$  ms for the pre-stimulus analysis, and  $-600$  to  $-300$  ms for the post-stimulus analysis. To ensure results were minimally affected by activity associated with motor preparation or task execution, all epochs where either the target disc was presented preceding, during, or following; and/or a response was made preceding, during, or following, the time window of interest were rejected. Artefacts, including blinks, eye movements, and muscle movements were identified and removed by BESA’s automatic artefact scanning tool, where epochs were rejected that 1) exceeded an amplitude threshold of 150  $\mu$ V, 2) contained amplitude jumps between any two sampling points of greater than 75  $\mu$ V, or 3) contained amplitude signals lower than 0.10  $\mu$ V. With these specifications, an average of 86.70% of epochs were included per participant (phase one:  $M = 85\%$ ,  $SD = 9.0$ ,  $range = 64\text{--}98\%$ ; phase two:  $M = 87\%$ ,  $SD = 10.0$ ,  $range = 60\text{--}100\%$ ,  $SD = 10.0$ ; phase three:  $M = 87\%$ ,  $SD = 10.8$ ,  $range = 58\text{--}99\%$ ). There were no differences in rates of epochs rejected between groups (IB versus aware participants) or across phases (all  $p > .47$ ).

### 2.4. Time-frequency transformation

Raw data were transformed into the time–frequency domain via complex demodulation as described in Papp and Ktonas (1977) and implemented in BESA’s source coherence module (Hoechstetter et al., 2003). Here, data in the time-domain are multiplied by a complex exponential at the frequency of interest and are then low-pass filtered with a finite impulse response filter to remove unwanted frequencies and thereby define the frequency range extracted (Hoechstetter et al., 2003). We sampled between 2 and 30 Hz with a resolution of 1 Hz and applied the filter in sampling steps of 50 ms.

## 3. Results

For event related potential findings concerning the visual awareness negativity and the P300, the reader is referred to the supplementary results. Overall, 45.2% of the total sample (14 participants) were inattentionally blind to the square array during phase 1, whereas all other participants reported awareness of the square array in phase 1. All participants reported having noticed the square in phase 2. Awareness of the square was measured with the questionnaire that was administered after each phase. Observers were coded as inattentionally blind if they rated their confidence in seeing the square pattern as a three or less, or if they otherwise could not provide evidence of noticing the square. Conversely, participants who reported noticing a square pattern or who rated their confidence in seeing the square pattern as a four or five were coded as aware. Note that two participants were classified as aware, despite a self-reported confidence rating of 3, due to both their open-ended responses and frequency ratings indicating they had frequently perceived

**Table 1**  
Confidence and frequency ratings for the square array.

Confidence	Very conf. I did not see it	Conf. I did not see it	Uncertain	Conf. I saw it	Very conf. I saw it
Phase 1	5	6	5	5	10
Phase 2	0	0	0	3	28
Frequency	<i>Never</i>	<i>Rarely</i>	<i>Infrequently</i>	<i>Frequently</i>	<i>Very frequently</i>
Phase 1	8	7	9	5	2
Phase 2	0	1	4	17	9

Note. # represents the frequency of responses (i.e. number of participants) at that rating.

**Table 2**  
Mean task performance across phases and groups.

	Accuracy	Reaction time	D prime
IB			
Phase 1	68.93% (18.40)	713 ms (121)	2.43 (1.27)
Phase 2	62.36% (24.69)	688 ms (98)	2.28 (0.74)
Phase 3	80.73% (12.81)	620 ms (76)	3.47 (0.83)
Aware			
Phase 1	68.15% (17.43)	706 ms (171)	2.55 (1.33)
Phase 2	65.22% (20.49)	730 ms (184)	2.81 (1.39)
Phase 3	75.76% (21.64)	658 ms (125)	3.70 (1.24)

Note. Standard deviation in parentheses.

the square. Table 1 reports the confidence and frequency ratings of participants for the square array.

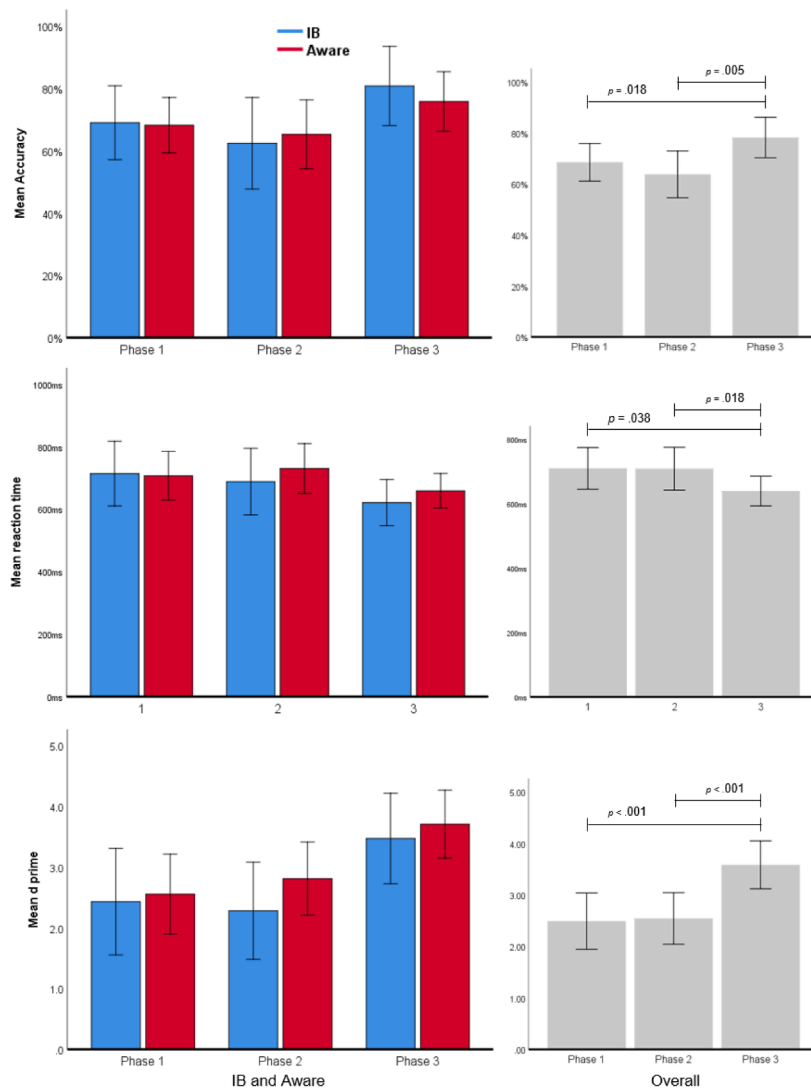
### 3.1. Task performance does not correlate with inattentional blindness

We first sought to establish whether performance on the distractor task (i.e. disc detection) could have impacted rates of inattentional blindness. To this end, separate repeated measures ANOVAs revealed no significant interaction between phase (phase 1, phase 2, phase 3) or group (IB, aware) on accuracy  $F(1.49, 34.24) = 0.558, p = .527$ , d prime,  $F(1.48, 33.98) = 0.537, p = .537$ , or reaction time,  $F(1.49, 34.26) = 0.530, p = .541$ , for the distractor task. There were additionally no significant main effects for group (IB, aware) on any task performance measures (all  $p > .52$ ). Thus, whether participants were subject to inattentional blindness of the square array was unlikely a result of attentional allocation to the distractor task (see Table 2). There was however a main effect for phase (phase 1, phase 2, phase 3) on all task performance measures (all  $p < .025$ ), suggesting that participants performed better at the diamond detection task in phase 3 than the disc detection task in phase 1 and phase 2 (see Fig. 2).

### 3.2. Pre-Stimulus alpha correlates with visual awareness

For our first analyses, we were interested in whether there was a general pre-stimulus alpha bias that differentiated IB from aware participants. We therefore examined differences between overall pre-stimulus activity by collapsing across stimuli (square + diamond + random array). Our reasoning was because the stimuli were presented in randomized sequences, any pre-stimulus effect that differentiates between IB and aware participants should occur independent of the upcoming stimulus type. The electrode group for pre-stimulus analyses was chosen based on the method of Pitts et al. (2012, also see Harris et al., 2018), i.e. mean alpha power over the entire epoch (−600 to +600 ms) across all electrodes from all participants and conditions pooled together. From this method, which ensured the electrode choice was orthogonal to the effect of interest, a group of right parietal-occipital electrodes was selected for analysis (P6, PO4, PO8, O2). Because of the right hemispheric bias of this cluster, we selected an additional comparable electrode cluster within the left hemisphere (P5, PO3, PO7, O1) to establish the laterality of any effect. We next ran a 2 (group: IB, aware)  $\times$  2 (hemisphere: left, right)  $\times$  3 (phase: phase 1, phase 2, phase 3) mixed factorial ANOVA assessing pre-stimulus (−500 to −200 ms) alpha (8 to 12 Hz), which revealed a significant interaction between group and phase,  $F(2, 24) = 12.287, p = 0.0002$ , but no significant interaction between group, phase, and hemisphere,  $F(2, 24) = 0.465, p = .634^1$ . Therefore, follow-up analyses combined electrode groups between hemispheres and revealed the main effect of IB on phase was due to significant between-subject differences in pre-stimulus alpha between IB and aware participants in phase 1,  $t(14) = 7.527, p = 0.000003$  ( $M_{\text{diff}} = 0.05, SE_{\text{diff}} = 0.006$ ). Between subject differences in phase 2 and 3 were not significant ( $> p 0.11$ ). Paired samples  $t$  tests revealed within-subject differences in IB participants across phase 1 and 2 ( $M_{\text{diff}} = 0.020, SE = 0.006, p = 0.018$ ), phase 2 and 3 ( $M_{\text{diff}} = -0.042, SE = 0.009, p = .002$ ), and phase 1 and 3 ( $M_{\text{diff}} = -0.022, SE = 0.005, p = .004$ ); and in aware participants across phase 1 and 2 ( $M_{\text{diff}} = -0.016, SE = 0.004, p = .006$ ),

<sup>1</sup> Note that there was a significant interaction between hemisphere and phase,  $F(2, 24) = 5.092, p = .01$ , which was due to a reduction in alpha power in phase 2 in the right hemisphere,  $t(14) = 4.912, p = .00002$ .



**Fig. 2.** Task Performance (Accuracy, Reaction time, d prime) Across Phases, *Note.* The “IB and aware” column illustrates task performance (accuracy, reaction time, d prime) between groups (IB, aware) from phase one to three. The “Overall” column demonstrates significant main effects (all participants combined) from phases one to three. Error bars represent  $\pm 2$  SE.

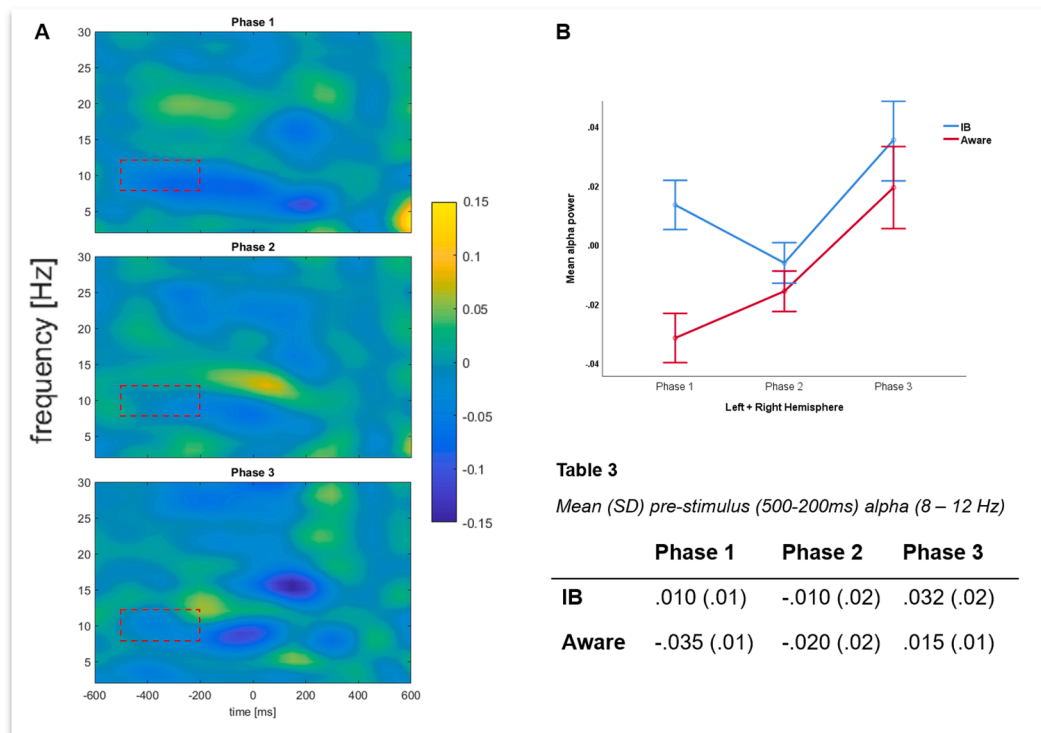
phase 2 and 3 ( $M_{\text{diff}} = -0.035$ ,  $SE = 0.005$ ,  $p = .0003$ ), and phase 1 and 3 ( $M_{\text{diff}} = -0.051$ ,  $SE = 0.006$ ,  $p = 0.00003$ ) (see Fig. 3).

These findings illustrate that, compared to those who were inattentively blind, self-reported awareness of the square array was associated with significantly reduced pre-stimulus oscillatory activity in the alpha-band. This effect is not likely to be a result of practice effects or generic individual differences because it was found both between- (IB vs. aware participants in phase 1) and within-subjects (phase 1 vs. phase 2 in IB participants). Second, no significant differences emerged between IB and aware participants in phase 2 or phase 3. In other words, there was a convergence of pre-stimulus oscillatory activity between groups after the critical manipulation associated with awareness of the square. We therefore consider this differential pattern of oscillatory activity as a preliminary neural predictor of inattention blindness. Note that each component of our analyses (brain region, time period, frequency) was selected *a priori*. However for completeness, we ran exploratory analyses to examine additional pre-stimulus activity that was noted upon visual inspection and found no significant effect ( $p > .15$ ).

### 3.3. Post-Stimulus alpha correlates with visual awareness

Our second analysis concerned whether there was a difference in post-stimulus activity between aware and inattentively blind participants, as recently observed by Harris et al. (2018). To determine the time window for our post-stimulus analysis, we ran independent samples t tests across the post-stimulus period with all phases combined (controlling for family wise error rate). Similar to



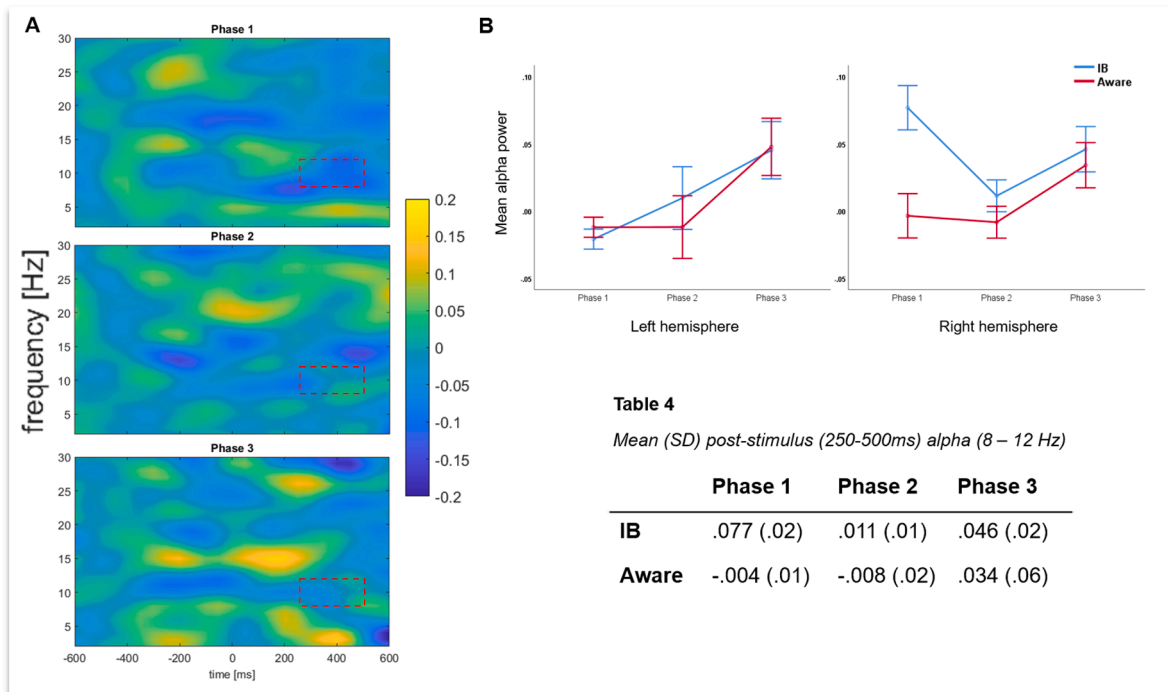


**Fig. 3.** A) Time frequency (2–30 Hz) representation (IB vs aware) of overall activity (square, diamond, random) across epoch in bilateral parieto-occipital (O1, O2, PO3, Po4, Po7, Po8, P5, P6). Red box represent area selected for statistical analysis. Differences across phases illustrates a reduction in pre stimulus alpha activity in phase 1 (Where aware and IB participants differ) relative to phase in bilateral electrode clusters. Error bars represents  $\pm 2$  SE. Table presents mean and standard deviation pre stimulus alpha power. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Harris et al. (2018), who noted an effect from approximately 300 to 700 ms, time differences from 250 ms to 500 ms in the post stimulus window were significant and were subsequently selected for analysis. A mixed factorial ANOVA on alpha power within this time window with IB and hemisphere as factors revealed a significant interaction between phase (phase 1, phase 2, phase 3), group (IB, aware), and hemisphere (left, right),  $F(2,24) = 6.758, p = .005$ , and phase and hemisphere,  $F(2, 24) = 11.806, p = 0.0003$ , suggesting a difference between hemispheres for the effect of interest. Because the interaction was significant, we examined each hemisphere separately. While post-stimulus alpha power in the left hemisphere electrode group was not significant ( $p = .303$ ), a mixed factorial ANOVA revealed a significant interaction in post-stimulus difference-related (square minus random) alpha power in the right hemisphere electrode group,  $F(2,12) = 12.128, p = .001$ . Follow-up analyses revealed the interaction was due to significant differences in post-stimulus power between subjects for phase 1,  $t(6) = 6.895, p = .00005$  ( $M_{\text{diff}} = 0.080, SE_{\text{diff}} = 0.012$ ). The between subject comparison for phase two was close to significant ( $p = .057$ ). The within-subject differences were significant in IB participants between phase 1 vs phase 2 ( $M_{\text{diff}} = 0.065, SE = 0.013, p = .015$ ) and phase 2 vs phase 3 ( $M_{\text{diff}} = -0.035, SE = 0.011, p = .046$ ), and in aware participants for phase 1 vs phase 3 ( $M_{\text{diff}} = -0.038, SE = 0.010, p = .029$ ) (see Fig. 4). These findings illustrate that, compared to those who were inattentively blind in phase 1, awareness of the square array was associated with significantly lower post-stimulus alpha power. As with our pre-stimulus finding, the directionality of this effect held both between- (IB vs. aware participants in phase 1) and within- subjects (phase 1 vs. phase 2 in IB participants). The effect was very similar to that reported by Harris et al. (2018), whereby alpha power in phase 2 reduced in the IB group to levels similar to the aware group in phase 1. Moreover, as with our pre-stimulus findings, there was a significant increase in both groups in phase 3, when the line segments became task relevant (see Fig. 4).

### 3.4. Alpha and task performance

Next, we ran two-tailed bivariate Pearson's correlations to determine whether pre- or post-stimulus alpha activity correlated with task performance (noting that we discarded epochs where the dim disc was presented and/or a response was made). Pre-stimulus alpha



**Fig. 4.** A) Time frequency (2–30 Hz) representation (IB vs aware) of difference activity (square minus random) across epoch in right hemispheric electrode group (O2, PO4, PO8, P6). Red box represents area selected for statistical analysis. Differences across phases illustrates a selective suppression of post stimulus alpha activity in phase 1 (relative to phase 2 and 3), likely reflecting spontaneous awareness of the square. B) mean post stimulus alpha across phases in left hemisphere (left) and right hemisphere (right) electrode clusters. Error bars represents  $\pm 2$  SE. Time frequency maps correspond with right hemisphere electrode group. Table presents mean and standard deviation pre stimulus alpha power. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

did not correlate with any task performance measures during any phase of the task. In phase one, post stimulus alpha correlated with reaction time,  $r = 0.627$ ,  $p = .002$ , and  $d$  prime,  $r = -0.434$ ,  $p = .044$ . In phase two, post stimulus alpha was close to significantly correlated with reaction time,  $r = 0.431$ ,  $p = .045$ . In phase three, post stimulus alpha did not significantly correlate with any task performance measure (all  $p > .11$ ).

#### 4. Discussion

The present study sought to examine whether pre- and post-stimulus alpha correlates with visual consciousness during IB. Findings demonstrated that, compared to those participants who reported not having perceived the square array when it was task-irrelevant, participants who were aware of the square showed a decrease in overall pre-stimulus alpha power and a decrease in post-stimulus alpha power uniquely associated with perception of the square. These effects held irrespective of whether awareness was spontaneous (i.e. between-subjects in phase 1) or cued via the questionnaire (i.e. phase 1 vs phase 2 in IB participants). In phase 3, when the line segments became task relevant, there was an increase in pre- and post-stimulus alpha power for both groups of participants. As per previous work [Pitts et al. \(2014\)](#), we also found the P300 for the square array during this phase (i.e. when it became task relevant, see supplementary results). Conversely, the visual awareness negativity was observed in those conditions in which subjects perceived the critical stimulus, yet the stimulus itself remained task irrelevant (i.e. phase 1 and 2 in the aware participants and phase 2 only in the IB group; [Pitts et al., 2012](#)). Several key elements of the task may provide explanations for how these results fit into the existing literature ([Hanslmayr et al., 2007](#); [Harris et al., 2018](#)).

##### 4.1. Pre-Stimulus alpha predicts awareness during inattention blindness

The pre-stimulus effect observed in the current study is consistent with previous findings on the relationship between pre-stimulus alpha and perception ([Hanslmayr et al., 2007](#)), yet unique in that no previous work has sought to establish the relationship between pre-stimulus alpha and IB. The novelty of this finding is underscored by the fact that it implies that neither task-relevancy nor the need



for report (Tsuchiya et al., 2015) are requirements for the relationship between pre-stimulus alpha and perception. Moreover, because performance was comparable between those who perceived versus failed to perceive the square, the decrease in alpha-power appears to be selectively associated with visual awareness of unexpected and task-irrelevant stimuli.

More contentiously, it might be argued that these findings provide evidence of a relationship between pre-stimulus alpha and visual awareness in the absence of anticipatory cuing. Alpha is often referred to as a mechanism of “anticipatory attention” (Foxe & Snyder, 2011) because its relationship with both attention and awareness are founded upon cuing tasks (Kelly, Lalor, Reilly, & Foxe, 2006; Samaha, Bauer, Cimaroli, & Postle, 2015; Thut et al., 2006; but see Wildegger, van Ede, Woolrich, Gillebert, & Nobre 2017). In general, a decrease in alpha is observed in the pre-stimulus interval in response to a cue in those instances where a stimulus is attended or perceived. Thus, a decrease in pre-stimulus alpha is interpreted as representing a cortical state of preparation for the optimal processing of task-relevant information. Notably, this leaves open the extent to which the effect is reliant on cuing. Recent work by Boncompte, Villena-Gonzalez, Cosmelli, and Lopez (2016) found that there was no significant difference in total alpha power between perceived versus not perceived stimuli without a spatial or temporal cue—though they did observe a significant lateralization effect.

In consideration of the implicit orienting that would occur given the static and spatially predictable arrangement of the line segments, we cannot claim with confidence that the findings reported here are independent from anticipatory mechanisms. Still, they do imply that pre-stimulus alpha is able to distinguish between stimuli which are consciously perceived versus those which are not perceived, even in the absence of top-down information regarding the stimulus—whether it be an explicit cue, task instructions, or prior knowledge. Moreover, our data show that any effect of pre-stimulus alpha is not limited to task-relevant information, as the square array was entirely irrelevant during phase one and two of the task.

#### 4.1.1. Alpha and task-irrelevant inhibition

How can a decrease in pre-stimulus alpha, which is typically thought of as representing a cortical state of preparation for task relevant processing, predict task *irrelevant* processing (i.e. task irrelevant visual awareness)? Current neuroanatomical models of alpha implicate an increase in alpha power in the cyclical removal of task-irrelevant and distracting information, thereby facilitating the processing of relevant information (Sadaghiani & Kleinschmidt, 2016). This understanding has emerged based on the finding that an increase in alpha contralateral to unattended visual regions occurs when there is competing input (Worden et al., 2000), but is absent when there is no competition for resources (Ikkai, Dandekar, & Curtis, 2016; Slagter et al., 2016). For example, Slagter et al. (2016) found that when only one side of the visual display was task-relevant and no competing input was presented, the typical increase in alpha over unattended or “irrelevant” regions was absent. Thus, one interpretation of our findings is that they reflect active suppression of to-be-ignored information. Active suppression might explain the increase in pre-stimulus alpha observed during phase two in those participants who spontaneously noticed the critical stimulus: an increase may have occurred here because distractor suppression was elicited when these participants were cued via the questionnaire to expect (and hence actively ignore) the stimulus.

This might similarly explain the increase in both pre- and post-stimulus alpha for all participants that was observed in phase three. That is, discrimination of the line segments might require inhibition to facilitate the processing of task-relevant shapes (i.e. the diamonds) from the “distractors” (i.e. the square) or random arrays. It must however be stated that the view that alpha is an active mechanism of distractor suppression has recently been challenged on the account that it has not been adequately differentiated from its role in tracking where attention is deployed (Foster & Awh, 2019). Indeed, the pattern of activity observed in participants who failed to notice the square in phase one would be expected based upon attending away from versus toward the critical stimulus, respectively: higher pre-stimulus alpha when the stimuli were not perceived and a decrease when they were perceived. The finding that alpha power increased in all participants in phase three might also be a mere consequence of the change in task that occurred, as a “passive” account of alpha might predict an increase in alpha if such regions were simply no longer involved in task-related processing. Ultimately then, it is unclear whether our findings reflect the allocation of attention (but see Antonov, Chakravarthi, & Andersen, 2020), active suppression (Hutchinson, Pammer, & Bandara, 2020), or perhaps even individual differences in other top-down processes that preceded the task altogether—though we are inclined to surmise former.

#### 4.1.2. Alpha and top-down predictions

Recent work by Mayer et al. (2016) found intriguing evidence of a role of alpha in top-down prediction formation regarding the identity of a stimulus. In their work, participants performed a stimulus detection task in which the predictability of a target stimulus's identity was manipulated to determine the effect of top-down prediction on detection thresholds. Notably, findings showed an *increase* in pre-stimulus alpha predicted visual awareness of the target once an expectation had formed and the identity of the stimulus could be predicted (Mayer et al., 2016). This brings to question whether similar predictive mechanism may explain the pre-stimulus alpha modulation in phase 3 of the current study, rather than e.g. gating mechanisms. However, more recent work by Wildegger, van Ede, Woolrich, Gillebert, and Nobre (2017) found that predictive cues related to the identity of a stimulus had no observed effect on alpha. The authors argued that differences between studies may be related to whether the prediction is informative for task-related responding, as the identity prediction in their work was orthogonal to the need for a response. An alternative interpretation is therefore that the increase in pre-stimulus alpha in phase 3 of the current study could reflect top-down prediction mechanisms regarding the critical stimulus's identity, as this is when the stimuli are informative for a decision or response.

#### 4.2. Post stimulus activity

The post-stimulus oscillatory results in the current study parallel those made by Harris et al. (2018). That a reduction in post-stimulus alpha correlated with awareness, despite the stimulus remaining task-irrelevant, implies the effect is not related to post

perceptual processes associated with report. Harris et al. (2018) arrived at a similar conclusion, citing that participants who were aware of the square array in the first phase had no knowledge that they would need to report on it in any manner. Interestingly, the “aware” group of participants in their work were informed of the square array prior to the experiment. One might argue that prior knowledge regarding the stimulus could have therefore invoked the critical stimulus with some form of “experimental” relevancy. In the current study, participants entered the experiment without any prior knowledge regarding the stimulus. Rather, we relied on participants noticing the square spontaneously, which may have provided a stronger control of processes associated with task relevancy. More notably, Harris et al. (2018) did not include the third phase of the task in which the line segments were task relevant. In the current study, post-stimulus alpha exhibited an increase in phase 3 when the line segments became task relevant. Note however that despite participants attending to and discriminating the diamond from other line segment arrays, we have no direct behavioural data to validate whether they were truly aware of the square array in phase 3. Thus, it is not possible to know definitively whether the increase in phase 3 for the square array in the post-stimulus interval could nevertheless be interpreted as, e.g. a reduction *relative* to instances where the square did not reach awareness, or rather if it reflects a legitimate increase in post-stimulus alpha presumably due to the stimulus becoming task-relevant.

#### 4.2.1. Memory?

It has been argued that, rather than demonstrating a failure of consciousness *per se*, IB may instead evidence a failure of memory (Wolfe, 1999) or a failure to cognitively “access” the information for report (Vandenbroucke, Fahrenfort, Sligte, & Lamme, 2014). In the current study, there was no reason for participants to cognitively access or store the information due to the task irrelevant nature of the stimulus (Pitts et al., 2012). Indeed, this underscores the novelty of exemplifying the correlation between alpha and awareness in the absence of the need for report (Tsuchiya et al., 2015). Though it is noteworthy that alpha positively correlates with working memory (Jensen, Gelfand, Kounios, & Lisman, 2002), as it has been argued (Hanslmayr et al., 2007; Romei et al., 2008) that some previous findings may reflect a memory component when reporting is delayed (Babiloni et al., 2006). In the current study, this might suggest the increase in alpha observed in phase 3 reflects memory storage associated with the square. A crude speculation then might be that our data provide putative neural evidence of a *lack* of a memory component in IB, because this increase occurred only in phase 3. Yet, this seems unlikely as alpha was already heightened in the IB group during phase 1; and the very nature of delayed reporting necessitates memory, in that participants would be required to remember the square array to report having perceived it. Thus, this interpretation seems unlikely.

The post-stimulus effect was similarly not likely a result of low-level sensory processing, as it was measured as the difference between the processing of the square and random array (Pitts, Metzler, & Hillyard, 2014). Examining the difference between the processing of the line segments when they are randomly oriented with when they form the percept of a square provides a control for sensory processing associated with the line arrays. In effect, any differences that emerge should be associated with perceptual processing of the square (e.g. grouping, Pitts et al., 2012) or the conscious processing of the square itself (Hutchinson, 2019). Similar findings have been made by Levy et al. (2013) and Magazzini et al. (2016), who both found a reduction in post-stimulus alpha distinguished different stages of awareness when controlling for the sensory processing between different perceptual stages. Each study used a methodology in which the sensory processing between stages was carefully matched, with the key difference between results found to be the level of processing associated: Levy et al. (2013) reported alpha marked the difference between partial (orthographic detection) relative to full (semantic categorisation) conscious perception, whereas Magazzini et al. (2016) reported alpha activity distinguished between a lack of versus partial conscious perception. While the present study did not use a graded definition of awareness, our findings corroborate that, in some manner, a reduction in post-stimulus alpha provides a reliable marker of the difference between unconscious and conscious processing of visual information.

#### 4.2.2. Recurrent activity or increased excitability?

It is unclear what the relative reduction in oscillatory power observed here might reflect. Suppression of alpha power in the post-stimulus time window has been thought to correspond with local recurrent processing confined to visual cortex (Magazzini et al., 2016), which remains a candidate of the NCC-proper (Hutchinson, 2019; Lamme, 2010). It was recently demonstrated via microstimulation that alpha-band activity propagates downstream in the feedback, as opposed to feedforward, direction of macaque visual cortex (van Kerkoerle et al., 2014); a finding that has since been established in human participants via magnetencephalography (Michalareas et al., 2016). While not synonymous, feedback is a key means of recurrent neural activity (Lamme, & Roelfsema, 2000). However, increased re-entrant activity would presumably lead to oscillatory synchronization, and therefore be associated with an *increase* in oscillatory power. Rather than reflecting recurrent processing, the decrease in post-stimulus alpha observed here might therefore reflect increased excitability (Klimesch et al., 2007). This would align with the view that a reduction in alpha power correlates with behavioural measures of detection performance as a result of indexing cortical baseline excitability (Iemi et al., 2017; Lange, Oostenveld, & Fries, 2013; Mazaheri & Jensen, 2010).

The timing of the post-stimulus activity roughly corresponded with the visual awareness negativity (or the “VAN”, see Railo, Koivisto, & Revonsuo, 2011) and the P300, two well-established ERP correlates of conscious visual awareness (Pitts et al., 2012; Railo et al., 2011). Indeed, in line with the findings of Pitts et al. (2012) and Pitts et al. (2014), here we observed both ERPs—the VAN was found in those conditions where participants were self-reportedly aware of the square, whereas the P300 only emerged during phase three of the experiment, when the square became task relevant (see supplementary results). Thus, our ERP results are entirely consistent with prior literature which showcase that the VAN is the earliest ERP signature of awareness, whilst the P300 is more likely a marker of post perceptual task related processing.

The alpha effect occurred within the same temporal window as that reported by Harris et al. (2018). We initially suspected that

differences in task demands or the visuospatial arrangement may have led to differences in the latency of the effect between studies. Harris et al. (2018) used a task similar to that of Pitts et al. (2014), in which participants were to respond to salient red patches that formed within a centrally presented line array grid, while the square array was lateralized to either the left or right visual hemifield. In contrast, both the distractor task and line arrays in the current study were based on Pitts et al. (2012). That the effect observed corresponds precisely with that of Harris et al. (2018) provides converging evidence that a reduction in post-stimulus alpha uniquely reflects an NCC-proper under conditions of IB that is not confounded by differences in task parameters.

## 5. Concluding remarks

Inattention blindness reveals that attention and prior knowledge are instrumental in shaping our conscious perceptual experience. Here, we have demonstrated a correlation between both pre- and post-stimulus alpha oscillations and conscious visual awareness under conditions of inattention blindness. That the association between a reduction in pre-stimulus alpha and visual perception remains, even in the absence of top-down information regarding the stimulus, implies alpha remains an NCC that is not confounded by task-relevancy nor report-related confounds—although there is nevertheless reason to suspect modulation of alpha occurs for the purpose of facilitating the processing of task-relevant information.

More broadly, it is an exciting and novel finding that a neural correlate of inattention blindness that occurs prior to the stimulus can be observed. Whether such a relationship holds for more traditional cases of inattention blindness, for example the gorilla in a basketball game (Simons & Chabris, 1999), or in circumstances of driver-related inattention blindness (Kennedy & Bliss, 2013), remains to be seen. On the other hand, the relationship between post-stimulus alpha suppression and consciousness does not appear to be confounded by post-perceptual processes associated with prior knowledge or report. It will be essential for future work to examine the mechanisms underlying such activity, as evidence is clearly converging to suggest alpha oscillations represents a legitimate candidate for an NCC-proper.

## CRedit authorship contribution statement

**Brendan T. Hutchinson:** Conceptualization, Investigation, Formal analysis, Writing - original draft, Writing - review & editing, Visualization. **Kristen Pammer:** Supervision. **Bradley Jack:** Supervision.

## Declaration of Competing Interest

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

## Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.concog.2020.103034>.

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