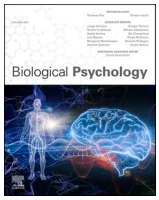
Biological Psychology 209 (2026) 109337

Contents lists available at ScienceDirect

Biological Psychology

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



Early automatic and late lateralised top-down mechanisms for 3D perception

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ARTICLE INFO

Keywords:
3D Shape
Depth perception
Attention
Laterality
Event-related potentials

ABSTRACT

Three-dimensional (3D) perception is a fundamental aspect of human vision, yet it is not entirely understood how the visual system uses monocular cues to create 3D objects from two-dimensional (2D) retinal input. Recent evidence suggests that early neural activity for depth perception occurs pre-attentively, whilst later 3D shape processing relies on the deployment of top-down attention. However, whether this later processing shows hemispheric lateralisation has received little attention. We utilised the N2pc component, a well-established marker of visual attention, to measure the neural correlates of attention to 3D shape. We hypothesised that greater attentional resources would be allocated to processing 3D compared to 2D shape, and that this activity would be lateralised to the right hemisphere, consistent with previous notions. As predicted, we found that 3D targets elicited a greater N2pc amplitude than 2D targets, but unexpectedly, this effect was only present over the left hemisphere. We suggest that this left lateralised attentional effect is consistent with suggestions that the left ventral visual pathway is dominant in processing 3D shape. Exploratory analysis also revealed a significant polarity reversal between 2D and 3D targets within the time-window of an early lateralised potential (N1pc), consistent with automatic attentional capture by depth information, even when it was task irrelevant. Taken together, these findings suggest that depth information first captures attention automatically, and that subsequent processing of 3D shape engages left lateralised top-down attentional mechanisms.

1. Introduction

The perception of three-dimensional (3D) shape is crucial for navigating and understanding our environment (Orban, 2011). Despite the importance of depth cues in understanding fall-related injuries (e.g., Clark et al., 1996; Schofield et al., 2017) and their application in fields such as computer vision (e.g., Liu et al., 2014), it is generally agreed that there remains a lack of research examining the neural processing of monocular compared to binocular depth cues (Gao et al., 2015; Séverac Cauquil et al., 2006). Here, we assess the time-course and lateralisation of 3D shape processing that arises from the monocular cue of shading, whereby 3D shape is constructed from 2D retinal input by utilising the shading patterns across an object (Kleffner & Ramachandran, 1992).

There is a large amount of evidence that suggests the right hemisphere is dominant in 3D perception defined by *binocular* cues (e.g., Baecke et al., 2009; Carmon & Bechtoldt, 1969; Durnford & Kimura, 1971; Franco & Sperry, 1977; Iwami et al., 2002; Negawa et al., 2002; Ward et al., 2016). Early research by Durnford and Kimura (1971) presented participants with two rods, one presented centrally, and another presented to the left or right of the central stimulus. Due to binocular depth cues, the stimulus presented in the periphery could appear either closer or further from the viewer than the central stimulus, and participants were asked to indicate whether the peripheral stimulus was closer or further from them than the central stimulus. They found that participants performed more accurately when the judged stimulus appeared on the left compared to the right of the central object. As a result, the authors suggested that there is a right hemispheric dominance in depth processing. This suggestion is consistent with a lesion study that found a deficit in 3D processing from binocular disparity in those with right hemispheric lesions, compared to a healthy control group and those with left hemispheric lesions (Carmon & Bechtoldt, 1969). The neural correlates of 3D processing have been studied by more recent research, for instance Iwami et al. (2002) presented participants with solid stereograms that elicited either static or dynamic stereopsis and

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https://doi.org/10.1016/j.biopsycho.2026.109337
Received 13 April 2026; Received in revised form 23 June 2026; Accepted 29 June 2026
Available online 2 July 2026

recorded the neural responses to both through functional magnetic resonance imaging (fMRI). They found that a region of the dorsal parieto-occipital cortex was sensitive to both static and dynamic stereopsis with a right hemispheric dominance, although no such hemispheric dominance was found in a region of the temporo-occipital junction that was active during dynamic stereopsis. Baecke et al. (2009) also found that depth from disparity evoked greater activity in the extra-striate cortex over the right compared to the left hemisphere, further evidencing a right lateralisation of 3D perception from binocular cues.

In contrast, evidence for a right hemispheric advantage in 3D processing defined by *monocular* cues is somewhat mixed. For instance, Murphy et al. (2016) showed that individuals with right posterior parietal lesions presented a deficit in 3D perception arising from binocular disparity, but 3D shape from motion appeared largely preserved in these individuals. Further, De Montalembert et al. (2010) reported that individuals with right temporo-parietal lesions were still able to report convex and concave shapes defined by shading, suggesting that 3D shape-from-shading can be recovered without a right hemispheric involvement. Gerardin et al. (2010) also used fMRI to assess the cortical areas implicated in 3D shape-from-shading and concluded that the intra-parietal sulcus (IPS) is critical in processing 3D shape, but no right lateralisation of this activity was reported. However, some evidence of a right lateralisation of 3D shape-from-shading comes from Taira et al. (2001). Here, the authors presented participants with coloured shaded stimuli and asked them to indicate either the colour of the object or the 3D shape of the object (convex or concave). They found that the right IPS was greater activated when participants attended to the 3D shape of the stimulus compared to when they attended to the colour. This is also interesting as this finding highlights the need for goal directed attention for a right hemisphere dominance of 3D shape-from-shading.

Despite this mixed evidence, research using event-related potentials (ERPs) have suggested that early neural activity for depth processing defined by monocular cues is lateralised to the right hemisphere (Gao et al., 2015; Matthews et al., 2025; Omoto et al., 2010; Séverac Cauquil et al., 2006; Séverac Cauquil et al., 2009; Yue et al., 2020). For instance, Séverac Cauquil et al. (2006) measured the amplitude of the P1 and N1 component whilst participants viewed images containing no depth or depth defined by perspective cues. They found a stronger negative N1 component for stimuli containing depth compared to stimuli that did not contain depth, and this difference was largest over the right IPS. Similar findings were also found by Gao et al. (2015) who observed a larger negative N1 component over right hemispheric sites for perspective drawings compared to planar graphics with no depth. Furthermore, Omoto et al. (2010) utilised ERPs to demonstrate early processing related to depth from texture gradients. Specifically, the authors found that stimuli that contained depth defined by texture gradients evoked a stronger positive P1 component than 2D stimuli, and this activity was distributed over right hemispheric sites. In the case of 3D shape-from-shading, it was previously demonstrated that an increased negativity in the N1 component for 3D compared to 2D shaded shapes was lateralised to the right hemisphere (Matthews et al., 2025). This effect only occurred when goal-driven attention was deployed to the stimuli, suggesting that this right lateralisation for 3D shape-from-shading represented early attention to shaded objects.

Although such studies provide evidence for a right lateralisation of early processing related to depth perception defined by monocular cues, it is not clear whether later processing for 3D shape perception is also lateralised. For instance, Omoto et al. (2010) found that 3D stimuli defined by texture also elicited a stronger positive amplitude P2 component, but this activity was distributed bilaterally. Moreover, Mamassian et al. (2003) asked participants to indicate the width of 3D strips across a shaded stimulus that could appear more narrow or wide dependant on the stimulus orientation. They found that the N2 component was modulated by the width of the 3D element of the stimulus, but this effect of the N2 component appeared bilateral. Interestingly, multiple hemispheric effects regarding the N2 component was reported by Gao et al. (2015). Here, the authors reported that a larger negative N2 component over the right hemisphere was observed for stimuli with depth information compared to stimuli with no depth information. However, they also observed a stronger negative N2 component for stimuli containing both 3D shape and depth, compared to stimuli with only depth information, but this activity was instead lateralised to the left hemisphere. This left hemispheric lateralisation is intriguing given the reports of a right hemispheric dominance in depth perception, but the authors attribute this left lateralisation as reflecting a dominance of areas in the ventral pathway of the left hemisphere in object processing (Livingstone & Hubel, 1988; Stewart et al., 2001). It was also recently observed that shaded stimuli that appeared concave elicited a larger negative N2 component compared to 2D stimuli, but this later processing for concavity was dependent on top-down attention (Matthews et al., 2025). Interestingly, this also supports the notion that early processing of depth-from-shading (e.g., the rapid extraction of depth information for figure-ground segregation) is a pre-attentive process, but later processing is required to perceive explicit 3D shape-from-shading, with this later process being reliant on the deployment of goal-driven attention (Matthews et al., 2025; Sapir et al., 2021). However, such a theory is at odds with early research which framed shape-from-shading as a purely pre-attentive process (e.g., Braun, 1993; Sun & Perona, 1996). As such, it is unclear whether later activity related to 3D shape processing is both lateralised and dependant on top-down attention.

Therefore, the current study aimed to investigate whether later activity for 3D shape processing is lateralised. We also sought to replicate the finding that this later processing for 3D shape-from-shading is reliant on the deployment of top-down attention. To do this, we measured the N2 posterior-contralateral (N2pc) component whilst participants indicated the location of a 2D or 3D target stimuli that appeared in the left or right visual field. The N2pc component typically occurs at latencies between ~200–350 ms post stimulus onset (e.g., Kiss et al., 2008; Liu et al., 2009; Woodman & Luck, 2003) and is characterised as a larger negative amplitude N2 component over the hemisphere contralateral to a target stimulus, compared to the ipsilateral hemisphere. The N2pc component has widely been linked to attentional processes such as distractor suppression (Luck & Hillyard, 1994) and target enhancement (Eimer, 1996; Li et al., 2018; Mazza et al., 2009). Interestingly, some work has found that the N2pc can also be influenced by hemispheric specialisations in the processing of specific stimuli, for instance a lateralisation of the N2pc to the left hemisphere has been reported when using words as the task stimuli (Dell'Acqua et al., 2007; Eimer, 1996; Liu et al., 2009), consistent with the dominance of the left hemisphere in processing language (Binder et al., 1997; Frost, 1999; Hirnstein et al., 2014). As such, the N2pc component is well placed to provide insight into both hemispheric lateralisation and attentional mechanisms related to 3D shape processing. Therefore, there were two hypotheses for the current experiment. Firstly, that there is late-stage processing that occurs for 3D shape-from-shading which is reliant on top-down attention, reflected by a larger negative amplitude N2pc for 3D compared to 2D targets. Secondly, in accordance with prior evidence suggesting a right hemispheric dominance in processing monocular depth cues (Omoto et al., 2010; Séverac Cauquil et al., 2006) and in particular shape-from-shading (Matthews et al., 2025; Taira et al., 2001), this later processing related to 3D shape-from-shading will be lateralised to the right hemisphere, reflected by a right lateralisation of the N2pc component when viewing 3D compared to 2D shape-from-shading.

2. Materials and methods

2.1. Pre-registration and power analysis

This study was pre-registered at asPredicted.com (https://aspredicted.org/qnc8-cwbg.pdf) before any data for the current experiment was

collected. To detect a difference of at least 0.5μV with 80% power, we planned to recruit twenty-four participants based on the adequate number of participants required to sufficiently power an analysis for repeated measures N2pc experiments (Jensen & MacDonald, 2023).

2.2. Participants

Thirty-six participants were recruited for the study to account for participants that need to be excluded for analysis, with all participants being psychology or sport science students. The age of the participants ranged from eighteen to twenty-six years of age ($M = 19.75$, $SD = 2.13$) and the cohort consisted of thirty females, with five male participants and one participant who did not conform to gender norms. Twenty-four participants reported being monolingual and all participants were right-handed. Thirty-two participants reported having no psychiatric conditions, whilst the remaining four participants reported a range of conditions including anxiety, dyslexia, depression and autism. Written fully informed consent was obtained from all participants, and course credits were given to participants for their participation. This study was approved by the Bangor ethics committee (ethics number: 2023–17317) and in accordance with our ethics approval no individuals were prevented from taking part in the study due to demographic information.

2.3. Task apparatus

The experiment was presented on a flat screen Samsung monitor at a resolution of 1920 × 1080 pixels and a refresh rate of 60 Hz. Presentation® software (Version 23.0, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com) was used to create and present the experiment and the EEG was recorded using the Biosemi ActiView program (https://www.biosemi.com/software_biosemi_acquisition.htm). A three-button response box was used for participant responses during the experiment, consisting of two upper buttons and one lower button.

2.4. Stimuli

The stimuli used for the current experiment are shown in Fig. 1. For the perception of 2D and 3D shape, we used the snowflake stimulus utilised in previous experiments (e.g., Matthews et al., 2025). The 3D snowflake stimulus uses an assumed light source position in combination with shading to produce the illusion of 3D shape. Specifically, when the bright edges of the stimuli are at the top of the object, participants report the object as appearing convex. When the stimulus is rotated to 180°, the bright edges of the object are positioned at the bottom of the stimulus, leading to the perception of concavity. Only the snowflake stimulus at 180° was used here, to produce the illusion of concave stimuli. This was because previous research found that attention was necessary for later processing related to concave but not convex shape (Matthews et al., 2025) and using only concave shape allowed us to satisfy the high number of trials necessary in N2pc experiments (Jensen & MacDonald, 2023). The 2D snowflake stimulus consisted of alternating bright and dark lines creating the impression of shading that is not congruent with the perception of concave or convex shape, but rather an ambiguous 2D shape. These stimuli have been used in previous studies and have been found to produce reliable perceptions of 2D and 3D stimuli (see Matthews et al., 2025). Participants were seated 120 cm away from the display. Both the 2D and 3D snowflake subtended a visual angle of 5° and were presented 3° either side of the fixation cross at the centre of the screen, as an N2pc has been shown to be produced using similar eccentricities (Papaioannou & Luck, 2020).[1] A white cross was used as the fixation point and subtended a visual angle of 0.5°. All stimuli and text were presented on a grey background (RGB: 128, 128, 128).

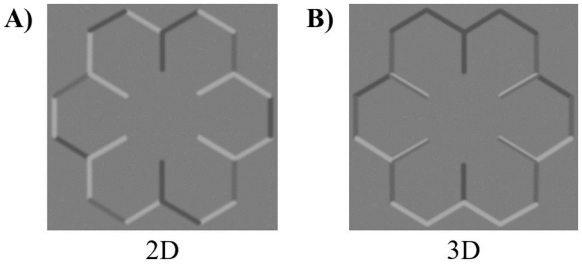

Fig. 1. 2D and 3D stimuli used for the current experiment. **A)** The 2D stimulus, consisting of alternating bright and dark lines to create the perception of an ambiguous 2D shape. **B)** The 3D stimulus, containing dark edges at the top and bright edges at the bottom to create the perception of concavity.

2.5. Design

The study consisted of a 2 (Shape: 2D and 3D) x 2 (Hemisphere: Left and Right) repeated measures design. The dependant variable of interest was the amplitude of the N2pc component, defined by the difference in activity between the contralateral and ipsilateral hemispheres relative to the target stimulus.

2.6. Procedure

Participants were sat in a faraday cage, and any electronic devices were removed from the participant. Once EEG set up was complete, participants were instructed to limit their eye blinks and eye movements as much as possible during the task. They were then presented with the experiment. Participants were first shown examples of the 2D and 3D snowflake stimulus and were asked whether they perceived the stimuli as flat (2D) or pushed-in (3D). They were then told that they would need to indicate the location of a target object on the screen, which would be determined by an instruction after each break. Specifically, participants were told that two objects will appear, one on the left and one on the right of a white cross, with one of them defined as a target, and participants were asked to respond with the left button if a target object appeared on the left, or with the right button if a target appeared on the right. They were reminded to keep their eyes focused on the central cross and not to look in the direction of the objects. Participants were then presented with 20 practice trials, consisting of 10 trials with the 2D stimulus as the target, and another 10 trials with the 3D stimulus as the target. Feedback regarding whether the response was correct or incorrect was given to participants only during practice trials. The experimental trials were then presented to participants, the procedure of which is shown in Fig. 2. Each trial began with the fixation cross displayed for 600 ms (+−100ms), before the 2D and 3D stimuli appeared either side of the cross for 200 ms. Both the target and distractor stimuli along with the fixation cross were then removed from the screen, and the trial ended either after the participant's response or after 3 s had passed without a response. Following an inter-trial interval of 1000 ms (+−300ms), the next trial began. After each block of experimental trials, a break screen was presented to participants, followed by a screen that informed participants about which shape was the target shape for the next block of trials. Following this, the next block of trials began. In total, there were 640 trials, with 160 trials for each location of each target shape. Each block contained 40 trials, with 20 trials containing

[1] We conducted a pilot experiment to test whether participants ($n = 21$) could perceive the 3D effect of the snowflake stimulus when presented in their peripheral vision, using a consistency measure developed by Andrews et al. (2013). We found no significant differences in the consistency of 3D shape judgements when the 3D snowflake was presented at eccentricities of −3° ($M = 3.75$, $SD = 1.98$), 0° ($M = 3.94$, $SD = 1.99$) and 3° ($M = 3.81$, $SD = 1.71$; $F(1.46, 26.32) = 2.31$, $p = 0.13$, $\eta_p^2 = 0.114$).

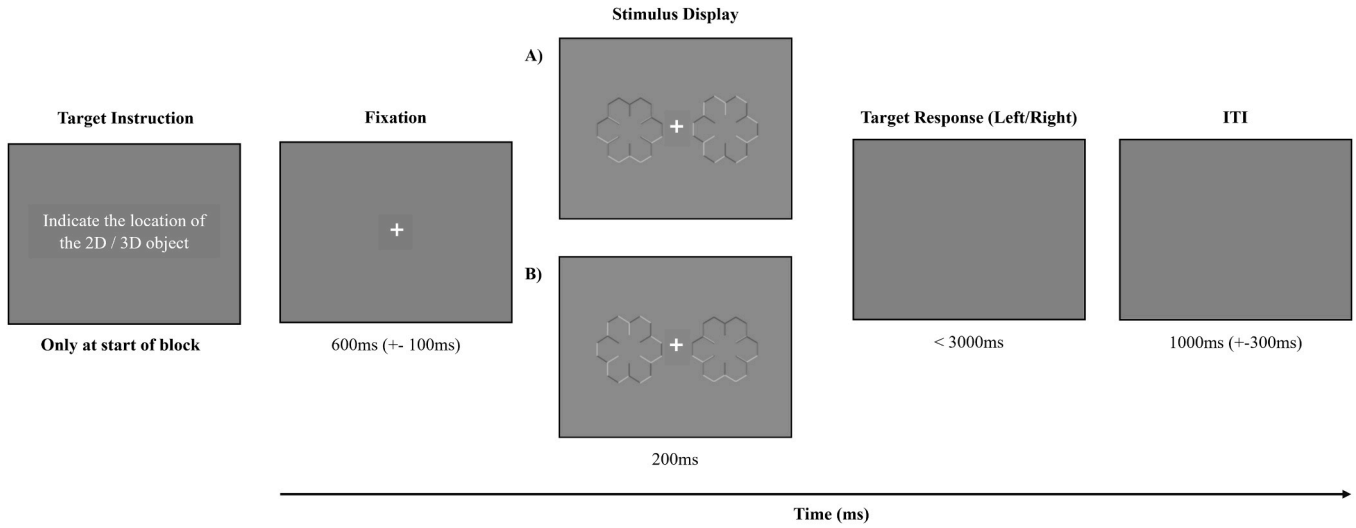

Fig. 2. Demonstrating the procedure of the experiment. Participants were assigned a target shape at the beginning of a block of trials, and they were required to indicate if the target shape appeared to the left or right of a fixation cross. **A**) The stimulus display with the 2D stimulus presented in the right visual field and the 3D stimulus presented in the left visual field. **B**) The stimulus display with the 2D stimulus presented in the left visual field and the 3D stimulus presented in the right visual field. *ms* = milliseconds, *ITI* = intertrial interval.

the target in the left visual field and 20 trials containing the target in the right visual field. The order of these trials was randomised, and blocks containing 2D and 3D targets was interleaved and counterbalanced. Once all blocks were completed, the experiment ended, and the participants were fully debriefed from the experiment. The session lasted approximately an hour for each participant, with EEG set-up and the experimental procedure taking approximately 30 min each. Participants were able to take as long as needed to rest during break screens in the experiment.

2.7. EEG acquisition and pre-processing

A 64 channel Biosemi Active-Two system (Biosemi B.V., Amsterdam, Netherlands) was used to gather EEG, which included the following channels placed in accordance with the extended 10/20 system: Fp1, AF3, AF7, F1, F3, F5, F7, FC1, FC3, FC5, FC7, C1, C3, C5, T7, CP1, CP3, CP5, TP7, P1, P3, P5, P7, PO3, PO7, P9, O1, Fp2, AF4, AF8, F2, F4, F6, F8, FC2, FC4, FC6, FC8, C2, C4, C6, T8, CP2, CP4, CP6, TP8, P2, P4, P6, P8, PO4, PO8, P10, O2, Fpz, Afz, Fz, FCz, Cz, CPz, Pz, POz, Oz & Iz. The EEG was recorded filter free, and the common-sense mode (CMS) and driven right leg (DRL) electrodes acted as the ground and reference electrodes during recording, with the data being re-referenced offline. Two flat electrodes were placed on the left and right linked mastoids, whilst a single flat electrode was placed under the participants left eye (EOG1) and two additional flat electrodes were placed by the participants' right and left outer canthus (EOG2 and EOG3) to record the horizontal electrooculogram (HEOG). All electrodes were connected to an A/C recorder. The offset of all electrodes was under 25μV before commencing recording and they were maintained under 30μV during recording, corresponding to the impedance of electrodes in the Biosemi system. The EEG was recorded at a sampling rate of 2048 Hz and decimated to 512 Hz once the recording session was finished.

The pre-processing was conducted using ERPLAB (v12.01; Lopez-Calderon & Luck, 2014) and EEGLAB (v2025.0.0; Delorme & Makeig, 2004) running in MATLAB (R2023a). First, we used an IIR Butterworth filter to apply a bandpass filter of 0.1–30 Hz to the data, with a roll-off slope of 12 dB/octave. The data was then re-referenced to the average signal of the left and right mastoids. Furthermore, the signal of electrode Fp1 was subtracted from the signal of electrode EOG1 to create the vertical electrooculogram (VEOG), whilst a bipolar HEOG channel was created by subtracting the signal of EOG3 from EOG2 (subtracting left HEOG from right HEOG). The data was segmented into epochs of −200–800 ms, with the onset of the event of interest occurring at 0 ms in the epoch, and a baseline correction of −200–0 ms applied to each epoch. Following this, we used ERPLAB to conduct a two-step procedure for removing artefacts in the data, similar to previous work (e.g., Luck, 2022; Papaioannou & Luck, 2020; Woodman & Luck, 2003). First, we used automatic artefact rejection with a window-to-window threshold criterion of 100μV and a window step of 100 ms to remove large artefacts between −200–400 ms post stimulus onset. We then performed a second round of artefact rejection to remove small horizontal eye movements. To do this, we rejected epochs that contained step-like artefacts in the bipolar HEOG between −200–450 ms post stimulus onset using a window step of 10 ms and a threshold criterion of 16μV. Furthermore, the data was visually inspected to ensure that all epochs in the dataset which contained clear artefacts had been rejected, and no additional epochs were rejected through manual inspection. We then averaged all the remaining trials for the participant to create their average ERPs for each condition, and we shifted these ERPs backwards by 40 ms to match the delay between the event of interest and the associated event-code. Only correct responses were included in the average ERPs for each participant, and trials where participants took longer than 1500 ms to respond were also removed from analysis. Contralateral minus ipsilateral difference waves were then created for each target location of each shape. Finally, grand-average ERPs for each condition were then created by averaging the average ERPs from all participants for each condition of interest.

We predicted an N2pc to be elicited at ~200–350 ms post stimulus onset. This is based on previous work showing that differences in processing between 2D and 3D shape-from-shading have been reflected by an N2 component that occurred at 290–350ms post stimulus onset (Matthews et al., 2025), and work showing the N2pc component to begin at around 200 ms post stimulus onset (e.g., Kiss et al., 2008; Liu et al., 2009; Woodman & Luck, 2003). To decide upon the exact time-window for the N2pc, we created a collapsed localiser (Keil et al., 2014; Luck & Gaspelin, 2017) that was made by averaging together all contralateral minus ipsilateral difference waves for each condition. We defined the time-window of the N2pc component by plotting 5 ms epochs of the collapsed localiser across topography maps, which were then visually inspected to identify the time points at which a posterior negativity appeared to onset and offset. This method is analogous to other papers specifying time-windows from collapsed localisers

(Beatty-Martínez et al., 2021; Linton et al., 2020). We ensured that the chosen time-window reflected a contribution of the N2pc component from each participant by manually inspecting the contralateral–minus-ipsilateral difference wave of each participant and checking that a negative deflection occurred for each participant within the time-window defined by the collapsed localiser. This is in line with research that has supplemented the collapsed localiser approach with inspection of individual waveforms (Acaster et al., 2021) and helps to ensure that the time-windows chosen from grand-average ERPs are representative of consistent components at the participant level (e.g., Tanner & Van Hell, 2014). As a result of this, the final time-window specified for the N2pc component in the current experiment was 210–350ms post stimulus onset, and this time window was subsequently used for analysis. Given that parieto-occipital electrodes are typically used to measure the N2pc component (e.g., Bacigalupo & Luck, 2019; Kiss et al., 2008; Oemisch et al., 2017), we measured the N2pc component in the current study from electrodes PO3, PO4, PO7 & PO8.

2.8. Data Analysis

To provide sufficient power for repeated measures experiments with the N2pc component, we required that participants had at least 96 trials in each condition after artefact rejection (Jensen & MacDonald, 2023). Indeed, the final ERPs all contained a sufficient number of average trials well above this number, including the ERPs for the following conditions: 2D target in the left visual field ($M = 130.33$, $SD = 16.15$), 2D target in the right visual field ($M = 129.58$, $SD = 18.09$), 3D target in the left visual field ($M = 134.29$, $SD = 17.57$) and 3D target in the right visual field ($M = 131.50$, $SD = 18.64$). Furthermore, mean differences in voltage between left and right targets in the bipolar HEOG channel were recorded during the time window of the N2pc component for 2D ($M = 1.06$, $SD = 2.55$) and 3D ($M = 0.52$, $SD = 1.98$) targets. Given that a difference in bipolar HEOG voltage between left and right targets of < 3.2 μV equates to < 0.1μV propagation at posterior electrodes (Luck, 2022), horizontal eye movements had minimal impact on the amplitude of posterior electrodes where the N2pc component was recorded in the current study.

The N2pc in the current experiment was measured from difference waves constructed by subtracting the waveform at electrodes over the ipsilateral hemisphere to a target stimulus from electrodes over the contralateral hemisphere (referred to here as contralateral minus ipsilateral waveforms). To examine if the amplitude of the N2pc differed between shapes and hemispheres, we followed our planned analysis of conducting a 2 × 2 (Shape x Hemisphere) repeated measures analysis of variance (ANOVA), with the amplitude of the N2pc as the dependent variable. By using this approach, it also allowed us to test if there was an asymmetry in the distribution of the N2pc component, whereby a larger negative amplitude N2pc may be present in one hemisphere compared to the other, representing a general neural mechanism for the task. Further, we examined interaction effects to assess laterality, reflecting whether the size of the difference between conditions (e.g., 2D and 3D shape) was larger in one hemisphere than the other. Any significant interaction effects were further explored by conducting paired samples *t*-tests between each shape over each hemisphere. In line with our hypotheses, we expected that there would be a greater negative amplitude N2pc component for 3D compared to 2D targets (significant main effect of shape), but this would be lateralised to the right hemisphere (indicated by a significant Shape x Hemisphere interaction with a significant follow-up *t*-test for N2pc amplitude over the right but not left hemisphere). Additional analysis was conducted in the same manner to investigate the latency of the N2pc component in each condition, defined by the peak latency of the N2pc component for each condition, measured from the latency at which the N2pc component showed the strongest negative amplitude for each participant in each condition. Finally, the same statistical tests were performed to examine if there were any behavioural effects between conditions, with accuracy and reaction times for each target in each location being calculated by averaging the mean scores from each participant. All analysis was carried out using R (v4.3.0; R Core Team, 2023) with an alpha value of.05 for significance.

2.9. Exploratory analysis: early lateralised potential (N1pc)

Visual inspection of the waveforms produced from 3D and 2D targets revealed a prominent early change in the contralateral minus ipsilateral waveform for each shape that proceeded the time-window of the N2pc component. Whilst we did not pre-register any additional analysis of the contralateral minus ipsilateral difference waves, this early activity is interesting due to notions that shape-from-shading consists of an earlier processing stage which is pre-attentive (e.g., Matthews et al., 2025; Sapir et al., 2021; Sun & Perona, 1996), and previous evidence for early and later stages of processing for depth and 3D shape (e.g., Gao et al., 2015; Kasai & Morotomi, 2001). Moreover, studies have demonstrated the presence of an N1 posterior-contralateral (N1pc) component that occurs before the N2pc component at parieto-occipital electrodes (e.g., Zinchenko et al., 2020; Zinchenko et al., 2024), suggesting that the processing of 2D and 3D targets may have influenced the characteristics of a known ERP component that occurs prior to the N2pc component. As such, we decided to explore whether the N1pc component was modulated by target shape (2D or 3D) in the current study.

Similar to our N2pc analysis, we chose to measure the N1pc component from parieto-occipital electrodes (PO3, PO4, PO7 & PO8) given that parieto-occipital electrodes have previously been used to measure the N1pc component (Verleger et al., 2012; Zinchenko et al., 2020; Zinchenko et al., 2024). As the polarity of the N1pc was negative for 3D shape and positive for 2D shape, we created a time-window for analysis by plotting 5 ms epochs of the collapsed contralateral minus ipsilateral waveform for each shape onto topography maps. The time-window was defined as the period at which the component appeared to onset and offset for both 3D and 2D shape, determined by manual inspection. This produced a time-window of 120–180ms post stimulus onset. There were also very minimal differences between left and right targets in the bipolar HEOG activity during this time window (2D: $M = 0.13$, $SD = 1.67$; 3D: $M = 0.17$, $SD = 1.86$), demonstrating that the N1pc component was not due to eye-movements during the experiment. The latency of the N1pc component for each shape was measured from the contralateral-minus-ipsilateral difference waves by recording the peak latency of a positive peak in the N1pc time-window for 2D targets and a negative peak at the same time-window for 3D targets for each participant. Finally, analysis of the N1pc component was carried out in the same manner as was done for the N2pc component (a repeated measures Shape x Hemisphere ANOVA for N1pc amplitude and latency separately).

3. Results

3.1. Participants

Of the original cohort, 5 participants were excluded from analysis due an excessive number of trials being rejected (e.g., fewer than 96 trials in any condition) because of eye artefacts, muscle movements, etc. Furthermore, 3 participants were removed as they did not perceive the intended 3D shape and therefore could not complete the task efficiently. Finally, participants with psychiatric conditions ($n = 4$) were removed as atypical functioning of attention in individuals with conditions such as depression has previously been reported (e.g., Keller et al., 2019), which may have influenced the results of the current study. The final cohort consisted of twenty-four healthy participants aged eighteen to twenty-six years old ($M = 19.67$, $SD = 2.17$), with twenty females and four males. All participants were right-handed and possessed no known psychiatric conditions. Fourteen participants were bilingual, and all participants had normal or corrected to normal vision.

3.2. Behavioural data

Fig. 3 shows the accuracy and reaction times for each shape in the left and right visual field. Accuracy for 3D targets ($M = 97.16\%$, $SD = 4.85$) was significantly greater than for 2D targets ($M = 95.40\%$, $SD = 6.35$) regardless of target location (main effect of shape: $F(1,23) = 6.44$, $p = .018$, $\eta_p^2 = .219$). However, there was no difference in accuracy between targets in the left ($M = 96.11$, $SD = 6.18$) and right ($M = 96.46$, $SD = 5.22$) visual field (main effect of target location: $F(1,23) = 0.92$, $p = .34$, $\eta_p^2 = .039$), and target location did not modulate a difference in accuracy between shapes (Shape x Target location interaction: $F(1,23) = <.001$, $p = .97$, $\eta_p^2 = <.001$).

Overall reaction times for 2D ($M = 818.38$, $SD = 117.02$) stimuli were slightly slower than for 3D ($M = 803.02$, $SD = 120.81$) stimuli, however this effect was only on the threshold of significance (main effect of shape: $F(1,23) = 4.01$, $p = .057$, $\eta_p^2 = .148$). Reaction times were however significantly quicker for right ($M = 799.21$, $SD = 124.50$) than left ($M = 822.19$, $SD = 112.41$) targets (main effect of target location: $F(1,23) = 8.74$, $p = .007$, $\eta_p^2 = .275$). Despite this, the ANOVA showed no evidence that target location mediated a difference in reaction times between shapes (Shape x Target location interaction: $F(1,23) = 2.86$, $p = .10$, $\eta_p^2 = .110$).

3.3. N2pc amplitude

A one sample *t*-test revealed that the contralateral minus ipsilateral waveforms averaged across all conditions were significantly different from zero during the time-window of the N2pc component ($t(23) = 5.21$, $p < .001$, $d = 1.09$), demonstrating that the task produced a reliable N2pc component. Fig. 4 shows the N2pc component for 2D and 3D targets collapsed across each hemisphere, to demonstrate the general effect of attention to 2D and 3D shapes. The overall amplitude of the N2pc was significantly greater for 3D ($M = -0.80$, $SD = 1.35$) than 2D ($M = -0.44$, $SD = 1.28$) targets (main effect of shape: $F(1,23) = 5.21$, $p = .032$, $\eta_p^2 = .185$), indicating that greater attention was allocated to identify 3D targets. However, there was no effect of asymmetry, with no significant difference in the amplitude of the N2pc over the left ($M = -0.84$, $SD = 1.35$) or right ($M = -0.39$, $SD = 1.26$) hemisphere (main effect of hemisphere: $F(1,23) = 1.70$, $p = .20$, $\eta_p^2 = .069$). Crucially, the ANOVA suggested that the difference in the amplitude of the N2pc component between shapes was greater in one hemisphere than another (Shape x Hemisphere: $F(1,23) = 2.78$, $p = .044$, $\eta_p^2 = .165$). This effect of laterality can be seen in Fig. 5.

Further analysis showed that over the left hemisphere, 3D targets elicited a significantly greater amplitude N2pc ($M = -1.30$, $SD = 1.17$) than 2D targets ($M = -0.39$, $SD = 1.39$; $t(23) = 3.17$, $p = .004$, $d = .66$). However, over the right hemisphere the difference in N2pc amplitude between 3D targets ($M = -0.29$, $SD = 1.35$) and 2D targets ($M = -0.49$, $SD = 1.18$) was not significant ($t(23) = 0.63$, $p = .53$, $d = .13$). Given that 3D shape elicited a significantly greater amplitude N2pc component than 2D shape only over the left hemisphere, this provides evidence of a left lateralisation of processing for 3D shape-from-shading. This left hemispheric lateralisation for 3D shape is shown in Fig. 6.

3.4. N2pc latency

The overall latency of the N2pc component did not appear to significantly differ between 3D ($M = 290.02$, $SD = 27.61$) and 2D ($M = 283.96$, $SD = 25.38$) targets (main effect of shape: $F(1,23) = 1.96$, $p = .17$, $\eta_p^2 = .078$). Similarly, there was no main effect of hemisphere ($F(1,23) = .68$, $p = .42$, $\eta_p^2 = .028$), with no significant difference between N2pc latency over the left ($M = 284.93$, $SD = 27.34$) or right ($M = 289.04$, $SD = 25.86$) hemisphere, suggesting that there was no effect of asymmetry in the latency of the N2pc component. However, there was a significant effect of lateralisation (Shape x Hemisphere interaction: $F(1,23) = 4.31$, $p = .049$, $\eta_p^2 = .158$), suggesting a difference in the latency of the N2pc component between shapes in only one hemisphere. Further analysis revealed that over the left hemisphere, the N2pc latency was later for 3D ($M = 293.90$, $SD = 25.47$) than for 2D ($M = 275.96$, $SD = 26.67$) targets ($t(23) = -2.49$, $p = .02$, $d = .52$), yet over the right hemisphere there was no significant difference in the latency of the N2pc component for 3D ($M = 286.13$, $SD = 29.62$) and 2D ($M = 291.95$, $SD = 21.70$) targets ($t(23) = 0.81$, $p = .42$, $d = .16$). This effect of lateralisation for the latency of the N2pc for 3D shape is shown in Fig. 7.

3.5. N1pc component (Exploratory Analysis)

As previously discussed (see 2.9), after inspection of the waveform we also carried out exploratory analysis on the earlier N1pc component on the basis of work suggesting that there is early pre-attentive processing for depth perception that proceeds processing for 3D shape (e.g., Matthews et al., 2025; Gao et al., 2015). The N1pc component for each shape is clearly shown in Fig. 8. One-sample *t*-tests revealed that for the time window of the N1pc, 3D targets elicited a negative lateralised potential that was significantly different from 0 ($t(23) = -3.11$, $p = .004$, $d = 0.30$) whilst 2D targets elicited a positive lateralised potential that was also significantly different from 0 ($t(23) = 5.03$, $p < .001$, $d = 0.32$). Results confirmed that the difference in the amplitude of the

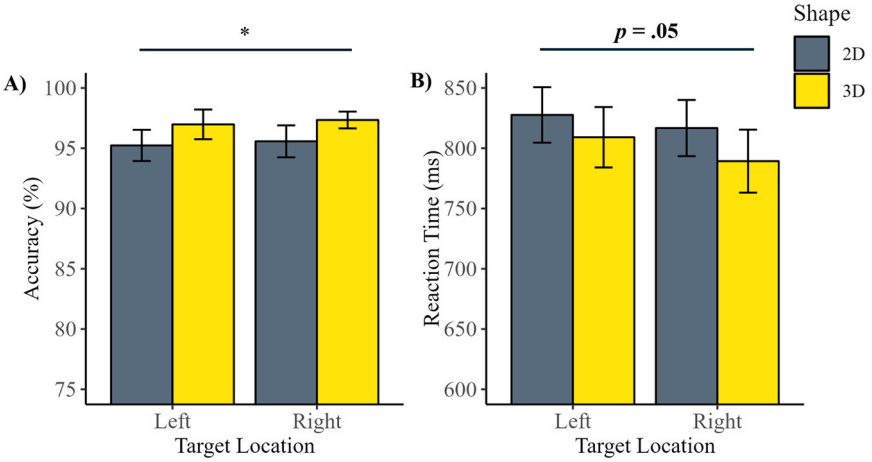

Fig. 3. Showing an overall higher accuracy for 3D compared to 2D targets, but differences in reaction times between 3D and 2D targets were on the threshold of significance. **A)** Mean accuracy for 3D and 2D targets in left and right target locations. **B)** Mean reaction times of correct responses for 3D and 2D targets in left and right target locations. * Differences between 3D and 2D stimuli significant to $p < .05$. *ms* = milliseconds. Error bars represent the standard error of the mean.

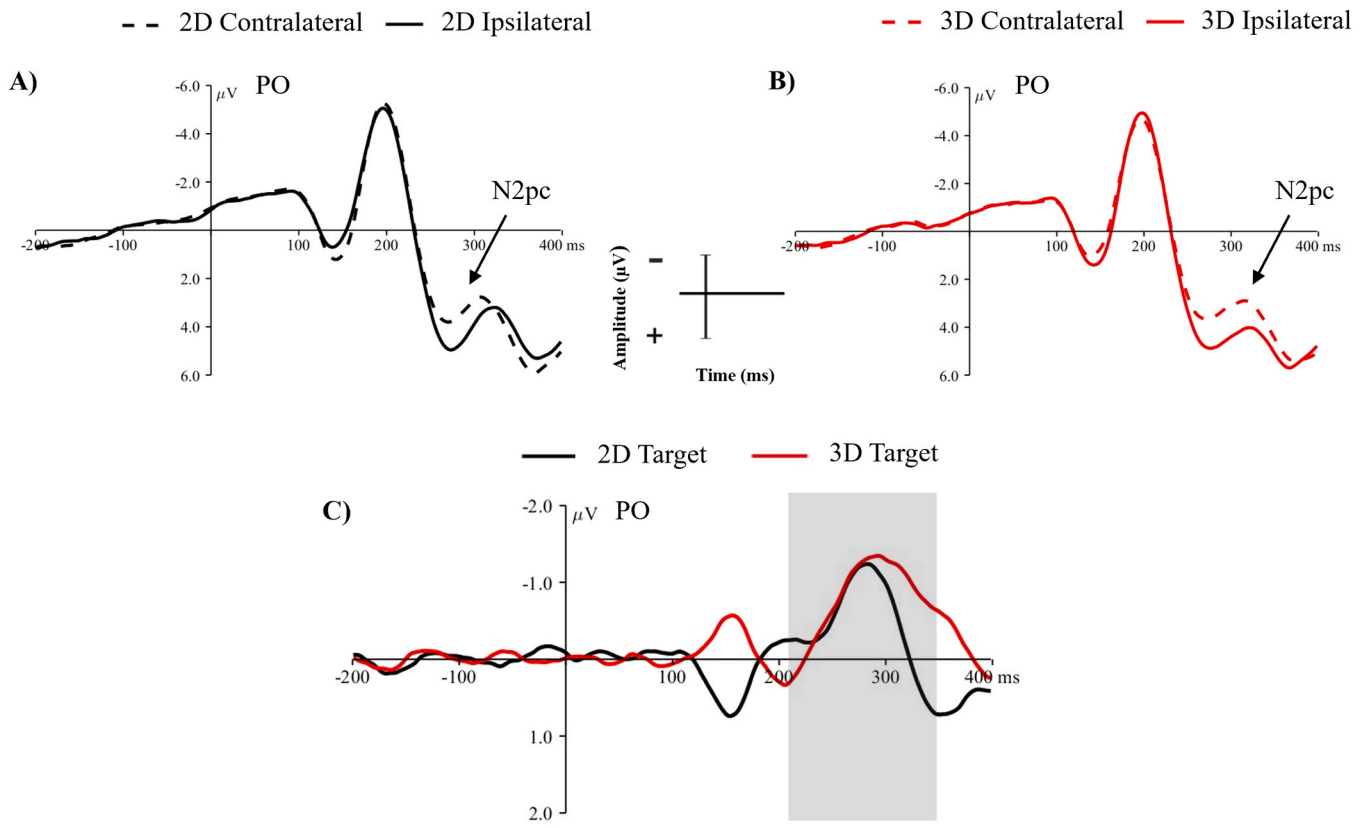

Fig. 4. Grand-average ERPs collapsed across hemispheres, showing differences in the N2pc for 2D and 3D shape. **A**) Contralateral and ipsilateral waveforms for 2D targets, averaged across the left and right hemisphere. **B)** Contralateral and ipsilateral waveforms for 3D targets, averaged across the left and right hemisphere. **C)** Contralateral minus ipsilateral target difference waves showing the N2pc component for 3D and 2D targets. The shaded regions show the time window used for analysis. All panels show the average of parieto-occipital electrodes (PO3/PO4 & PO7/PO8). *μV* = microvolts, *ms* = milliseconds.

N1pc was significantly different for 3D ($M = -0.32$, $SD = 1.08$) and 2D ($M = 0.42$, $SD = 1.32$) targets (main effect of shape: $F(1,23) = 20.48$, $p < .001$, $\eta_p^2 = .471$). However, no asymmetry in the amplitude of the N1pc was observed (main effect of hemisphere: $F(1,23) = .06$, $p = .80$, $\eta_p^2 = .003$) and no laterality effects were observed (Shape x Hemisphere interaction: $F(1,23) = .70$, $p = .41$, $\eta_p^2 = .029$). Regarding the time course of the N1pc component for each shape, whilst the latency of the N1pc for 3D targets ($M = 150.37$, $SD = 14.79$) was slightly earlier than for 2D targets ($M = 152.83$, $SD = 12.98$), this difference was not significant (main effect of shape: $F(1,23) = 1.58$, $p = .22$, $\eta_p^2 = .064$). We also did not find any evidence of an asymmetry in the latency of the component (main effect of hemisphere: $F(1,23) = 2.21$, $p = .15$, $\eta_p^2 = .088$) or that hemisphere mediated a difference between the latency of the N1pc component for each shape (Shape x Hemisphere interaction: $F(1,23) = 1.24$, $p = .27$, $\eta_p^2 = .051$).

4. Discussion

The aim of the current study was to investigate if late-stage processing for 3D shape is not only reliant on top-down attention but is also a lateralised process. To test this, we asked participants to identify the visual field in which a target shape (2D or 3D) was present, whilst we measured the N2pc component as an index of top-down attention to the target stimulus. We found that a larger negative amplitude N2pc component was elicited by 3D compared to 2D targets, consistent with predictions. Surprisingly, we found that this stronger negative N2pc component was found for 3D compared to 2D targets over the left, but not the right hemisphere. Given that the latency of the N2pc was also later for 3D compared to 2D targets over the left hemisphere only, our results suggest that attention enhanced the processing of 3D targets in the left, but not right hemisphere. As behavioural performance appeared to be overall better for 3D than 2D targets, we suggest that this left hemispheric lateralisation of the N2pc component represents a dominance of the left hemisphere in processing 3D shape-from-shading rather than additional effort being required to identify 3D targets in the right compared to the left visual field. To our knowledge, this is the first time that top-down attention for 3D shape defined by monocular cues has been found to be lateralised to the left hemisphere. Interestingly, exploratory analysis also found a significant polarity reversal of the earlier N1pc component between 3D and 2D targets, suggesting differences in early processing of 3D and 2D shape. The implications of these findings are discussed in detail below.

As predicted, we found a larger negative amplitude N2pc component elicited by 3D compared to 2D targets, suggesting that attention enhanced the processing of 3D shape at a late stage in processing. This is in line with previous findings which suggested that top-down attention is necessary for late-stage processing for 3D shape-from-shading (Matthews et al., 2025; Sapir et al., 2021). We propose that the increased negative amplitude N2pc component for 3D targets here represents attention specifically for 3D shape processing (e.g., processing convexity or concavity) rather than depth processing (e.g., relative distance). This account is consistent with evidence showing that processing of 3D shape information occurs after 200 ms following stimulus onset. For instance, Kasai and Morotomi (2001) recorded ERPs whilst participants attended to either depth or 3D form created from random-dot stereograms. The onset of selection negativities associated with attention to depth occurred at around 175 ms post stimulus onset, whilst attention to 3D form elicited a selection negativity that onset approximately 200 ms post stimulus onset. Moreover, Gao et al. (2015) found a greater N2 component at 290 ms was elicited from stimuli

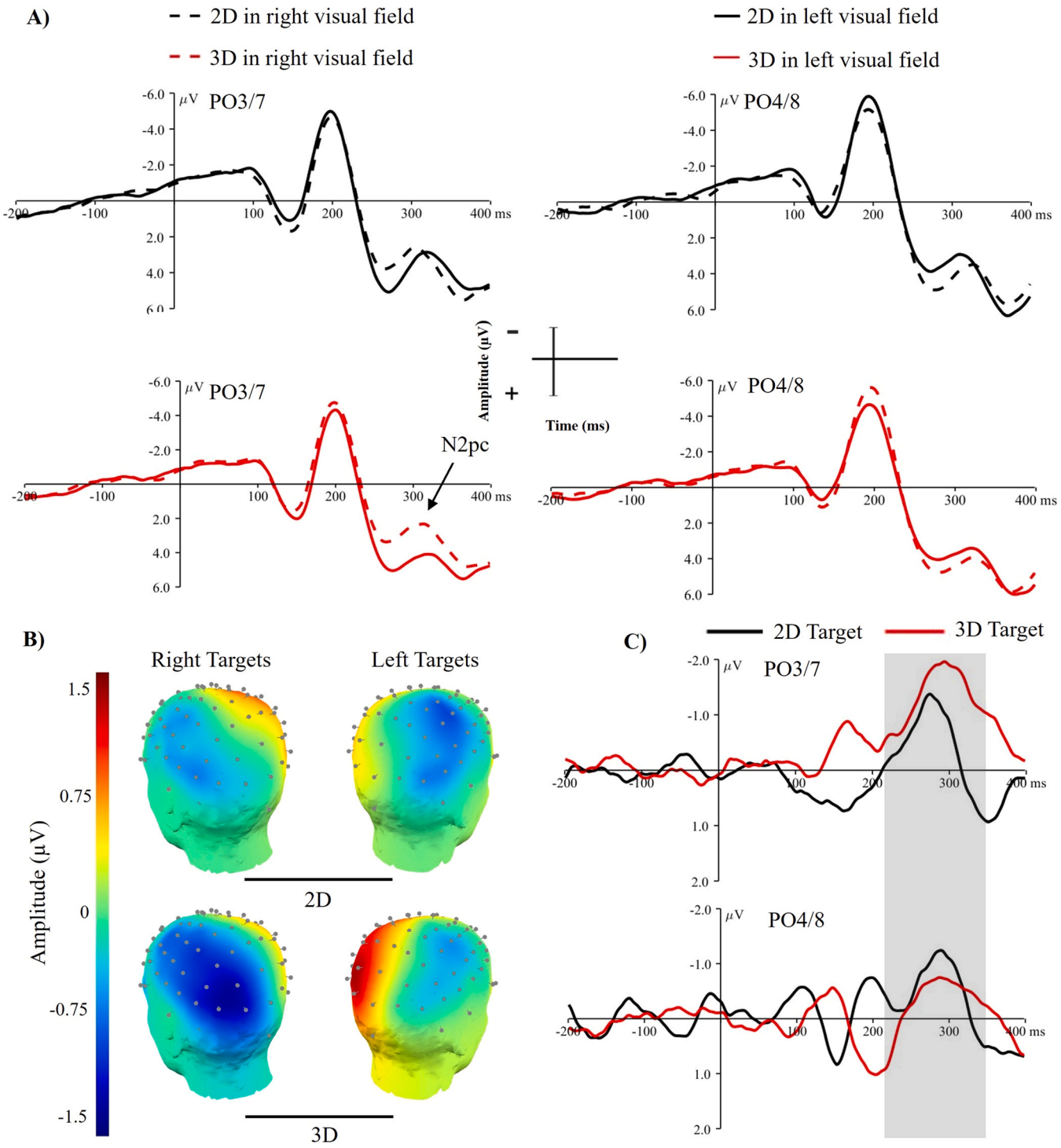

Fig. 5. Demonstrating a larger negative N2pc component for 3D compared to 2D shape over the left hemisphere. **A)** ERPs from the average of electrodes over the left (PO3/PO7) and right (PO4/PO8) hemisphere, demonstrating the presence of the N2pc component. **B)** Topography maps showing the mean voltage of contralateral minus ipsilateral difference waves for each shape across the scalp during the time range of the N2pc component. **C)** Contralateral minus ipsilateral difference waves highlighting the N2pc component for each shape, with PO3/7 showing left hemispheric activity and PO4/8 showing right hemispheric activity. The shaded region shows the time window used for analysis. *μV* = microvolts, *ms* = milliseconds.

containing 3D shape compared to stimuli only containing depth information. These results are congruent with other suggestions from Kingdom et al. (1999) that 3D form occurs later than depth and is reliant on higher level processing. Therefore, we suggest that the N2pc component here reflects top-down attention for target enhancement of 3D shape necessary for the recovery of explicit 3D shape-from-shading.

The results of this experiment also contribute to furthering our understanding of the lateralisation of 3D shape processing from monocular cues (e.g., Gao et al., 2015; Matthews et al., 2025). We observed that the N2pc component for 3D shaded targets was lateralised to the left hemisphere. Whilst this contrasts with work suggesting a right hemispheric dominance in 3D processing, this is likely due to methodological differences between the current and previous studies. For instance, some work has used fMRI to argue for a right hemispheric

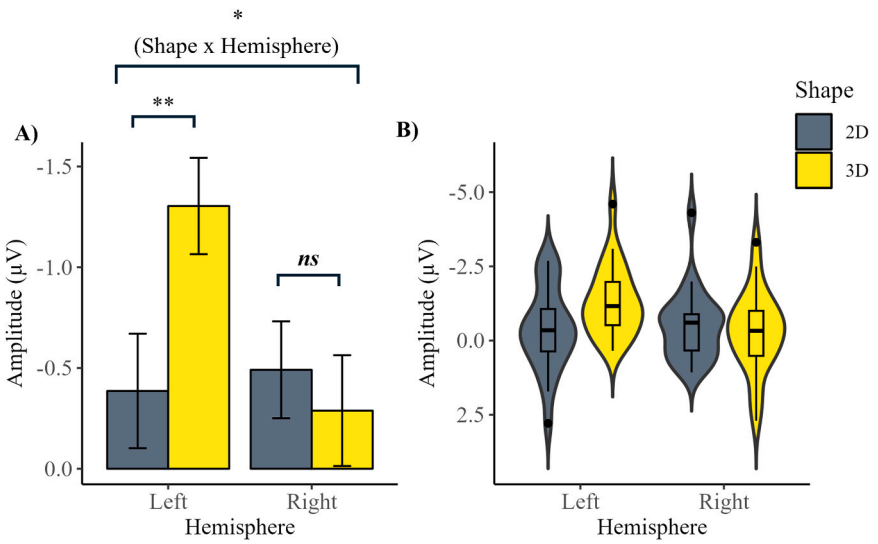

Fig. 6. Showing a significantly larger negative amplitude N2pc component for 3D shape only over the left hemisphere. **A)** Mean amplitude of the N2pc component over each hemisphere. **B)** Violin and boxplots showing the distribution of the N2pc amplitude over each hemisphere. * Significant to $p < .05$, ** Significant to $p < .01$, *ns* = not significant ($p > .05$). μV = microvolts. Error bars represent the standard error of the mean.

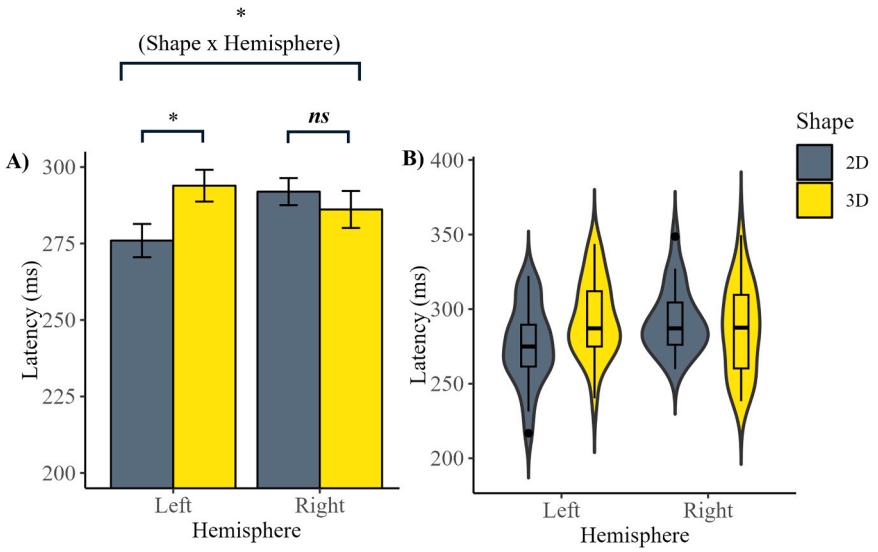

Fig. 7. Demonstrating a significantly later N2pc component for 3D shape only over the left hemisphere. **A)** Mean latency of the N2pc component over each hemisphere. **B)** Violin and boxplots showing the distribution of the N2pc latency over each hemisphere. * Significant to $p < .05$. *ns* = not significant ($p > .05$). *ms* = milliseconds. Error bars represent the standard error of the mean.

dominance of 3D perception (e.g., Baecke et al., 2009; Iwami et al., 2002; Taira et al., 2001), which may not have shown the role of the left hemisphere in late-stage processing for 3D shape processing due to the low temporal resolution of the hemodynamic response (Lindquist et al., 2009). This is also important as our stimuli were very similar to that used by Taira et al. (2001) in an fMRI study, which both consisted of shape-from-shading stimuli containing a single level of depth (e.g., only convexity or concavity). Therefore, it is likely that using ERPs to assess the time-course of neural processing for 3D perception in the current study allowed us to detect a dominance of the left hemisphere in 3D processing at a specific late-stage in processing, which may not have been represented in previous fMRI studies. Furthermore, whilst our findings are consistent with Gao et al. (2015) who found a left hemispheric dominance of the N2 component for 3D shape processing, it is inconsistent with some other ERP research. For instance, in our previous work (Matthews et al., 2025) we found a bilateral N2 component related to shape-from-shading. However, the 3D stimuli in our previous study were always presented at central fixation, rather than in the periphery as is the case in the current study. Given that the presentation of stimuli in the left and right visual field is a well-used paradigm to investigate hemispheric lateralisation (e.g., Jończyk, 2015; Takamiya et al., 2020; Yovel et al., 2003), this could explain why we found a left lateralised N2pc component for 3D shape processing in the current study.

Interestingly, we suggest that our finding of a left lateralised N2pc component for 3D shape processing may be related to the dominance of the left hemisphere in fine-grained, local feature processing. Previous work has used hierarchal structural stimuli consisting of both global and local shapes, typically finding that performance on tasks requiring the detection of local features is better when the local information appears in the right visual field or on the right side of an object (Christie et al., 2012; Yovel et al., 2001). Electrophysiological evidence has also demonstrated that global 3D shape is processed rapidly compared to local 3D shape, as observed by modulations of the N1 and N2 component (Leek et al., 2016). Processing for local 3D shape was also lateralised to

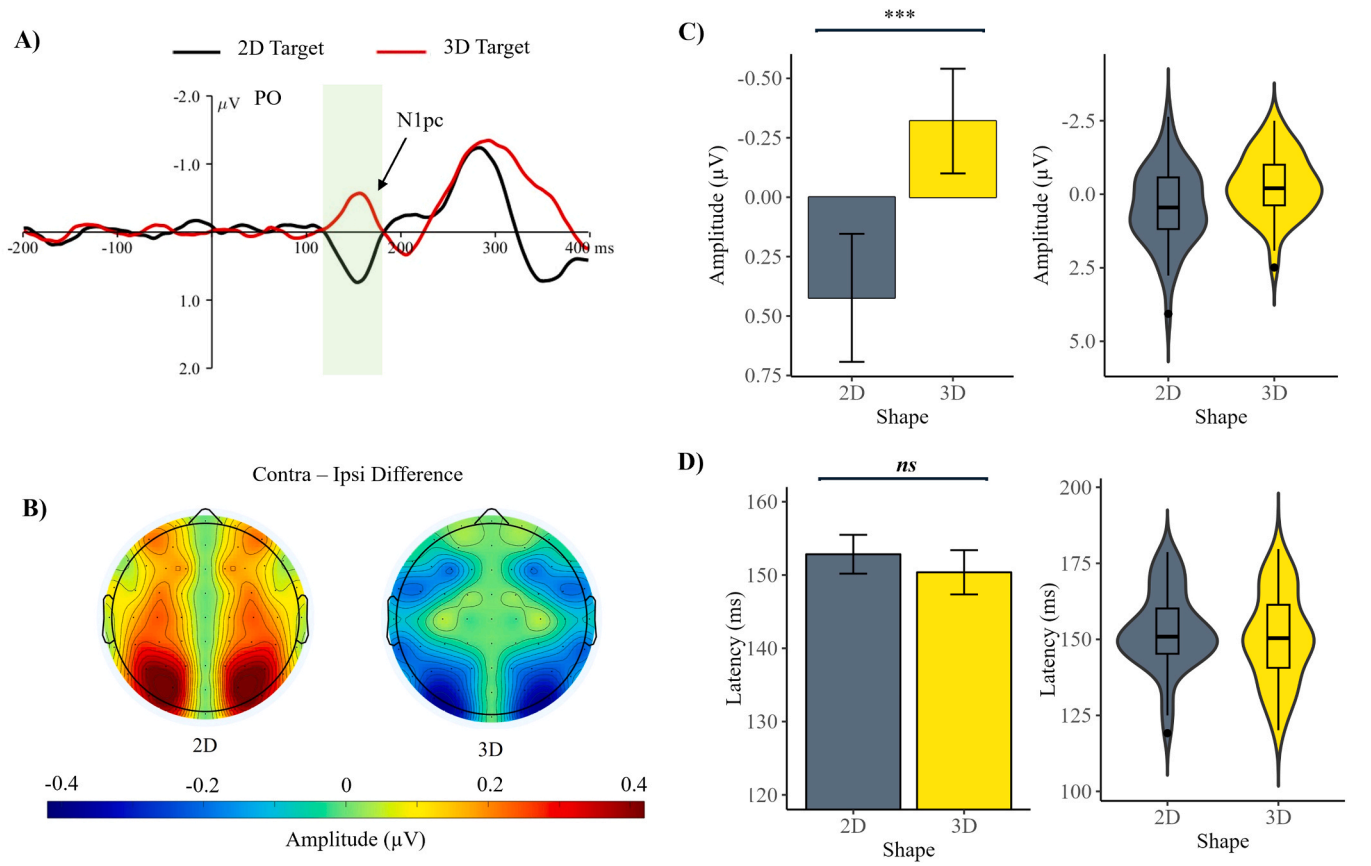

Fig. 8. Showing the N1pc polarity reversal for 2D and 3D targets. **A)** Contralateral minus ipsilateral difference wave collapsed across hemispheres, demonstrating the time-window used for N1pc analysis. The waveform is an average of all parieto-occipital electrodes (PO3/PO4 & PO7/PO8). **B)** Topography maps showing the average voltage of the N1pc for each shape during the time window of the component. Due to the nature of the collapsed contralateral minus ipsilateral difference waves, each hemisphere is a mirror image of one another. **C)** Bar and violin plots demonstrating the significant difference in N1pc amplitude between 3D and 2D shapes. **D)** Bar and violin plots demonstrating no significant difference in N1pc latency between 3D and 2D shapes. *μV* = microvolts, *ms* = milliseconds. Error bars represent the standard error of the mean.

the left posterior occipital-temporal cortex, consistent with suggestions of left hemispheric dominance in fine-grained, local feature processing and the involvement of the right hemisphere in course, global feature processing (Christie et al., 2012; Peyrin et al., 2003; Peyrin et al., 2004). Given that a right lateralisation of depth processing has been found at the time of the N1 component (Gao et al., 2015; Matthews et al., 2025; Séverac Cauquil et al., 2006) and the left lateralisation of the N2pc in the present study for 3D shape processing, these findings may converge to support the notion of coarse to fine object processing (Hegde, 2008; Peyrin et al., 2004; Skyberg et al., 2022), specifically for 3D shape processing (Leek et al., 2016; Menz & Freeman, 2003). As such, areas of the right hemisphere may provide a rapid but coarse representation of depth structure to support ongoing processing for fine-grained analysis of 3D shape at left hemispheric sites.

The findings here also inform a current discussion regarding the neural pathways supporting 3D shape-from-shading, as the left hemispheric dominance of 3D shape processing in the current study is likely to have been generated in areas of the ventral visual pathway. Gao et al. (2015) suggested that given the left lateralisation of an N2 component for 3D shape in their study, that the ventral pathway in the left hemisphere is specialised in processing 3D shape. Supporting evidence for this may come from work examining topographical features. For instance, it has found that the left temporal gyrus is specialised in processing topographical features such as holes (Wang et al., 2007). Given that concavities are vital in assessing topographical features (Cate & Behrmann, 2010), it is likely that areas involved in topographical processing would also be involved in the processing of 3D shape. Moreover, work has also found areas of the ventral pathway to be involved in the processing of 3D shape-from-shading, such as area V4 (Arcizet et al., 2009) and the lateral occipital complex (LOC; Kourtzi et al., 2003). This is interesting, as the N2pc component has been suggested to be generated by areas of the ventral visual system, particularly in V4 and the LOC (Hopf et al., 2006). Therefore, we propose that the left lateralisation of the N2pc component for 3D shape-from-shading observed in the current study likely originated from a dominance of the ventral visual pathway in processing 3D shape, highlighting the notion that the ventral visual pathway plays a critical role in 3D object perception.

Such a suggestion that ventral visual areas are specialised in the processing of explicit 3D shape processing aids in addressing the discrepancy in findings regarding the neural mechanisms of shape-from-shading. For example, research has indicated that parietal areas in the dorsal pathway such as the IPS are crucial for the processing of 3D shape-from-shading (e.g., Gerardin et al., 2010; Taira et al., 2001), whilst other work has instead indicated that ventral areas such as the LOC and inferior temporal gyrus (ITG) are key in extracting 3D shape-from-shading (Georgieva et al., 2008; Gillebert et al., 2015; Kourtzi et al., 2003). We suggest that although parietal areas such as the IPS undeniably play a critical role in 3D shape-from-shading, enhanced processing from top-down attention in areas of the ventral visual pathway is required for the perception of explicit 3D shape, at least in the case of concave objects presented in the current study. This is strengthened by work demonstrating that volume loss in the posterior inferior temporal cortex is associated with an impairment in the perception of 3D shape-from-shading in those with posterior cortical

atrophy (Gillebert et al., 2015). However, the ability to perceive 3D shape-from-shading was largely preserved in neglect patients with temporo-parietal lesions (De Montalembert et al., 2010). Therefore, a greater understanding of the role of the ventral and dorsal pathways in the processing of 3D shape-from-shading is necessary to further models of 3D shape perception.

Along with our N2pc findings, we found an N1pc component that distinguished between 3D and 2D targets at 120–180ms post stimulus onset. For 3D targets, this component was negative in amplitude, whilst for 2D targets this component's polarity was reversed. Whilst previous research has found an N1pc component between latencies of 80–190ms (Casiraghi et al., 2013; Kayser & Tenke, 2015; Verleger et al., 2012; Zinchenko et al., 2020; Zinchenko et al., 2024), interestingly some have suggested that the automatic capture of attention to a target in the left or right visual field leads to a negative N1pc, whilst misguidance of attention to the incorrect visual field causes a polarity reversal in the N1pc component (e.g., Zinchenko et al., 2020; Zinchenko et al., 2024). In the context of the current experiment, the negative N1pc for 3D targets, and a polarity reversal for 2D targets, suggests that 3D shape automatically captured attention. In 3D target trials, attention was automatically shifted to the target, producing a negative N1pc, whilst in trials with 2D targets, attention was misattributed to 3D shape and needed to be reoriented to the 2D target, resulting in a positive N1pc. This proposal is in line with research demonstrating 3D shape to consist of a pre-attentive element (Kleffner & Ramachandran, 1992; Sun & Perona, 1996), which occurs early in processing (Matthews et al., 2025) and acts as a guiding feature for attention (Wolfe & Horowitz, 2017). Such suggestions may also help to explain why there is evidence for an advantage for detection and localisation tasks that appear near in depth to the observer (near-advantage; e.g., Ahsan et al., 2022), but evidence for a near-advantage for discrimination tasks is mixed (Britt & Sun, 2024). That is, the near-advantage for detection and localisation tasks could result from the automatic bias of spatial attention to depth information, which facilitates the completion of detection and localisation tasks. However, discrimination tasks, which are thought to more heavily involve the ventral visual system (Lambert & Wootton, 2017), may be reliant on top-down attentional systems that are not automatically captured by depth information but are rather used for higher-level analysis of object features. Our findings not only establish that early depth processing of 3D shape automatically captures attention but also highlights the value of the N1pc as a tool to investigate which object features guide visual attention.

It is important to acknowledge some of the limitations of the current work, particularly the generalisability of the left hemispheric lateralisation of attention for 3D shape-from-shading. For instance, the stimuli used in the current experiment consisted of either 2D or concave (3D) shaded stimuli. However, given that previous work has found significant differences in the neural processing of convex and concave stimuli (Haushofer et al., 2008; Matthews et al., 2025), and the presence of a convexity prior in shape-from-shading (Langer & Bülthoff, 2001) it is unclear whether this left lateralisation would generalise to convex shape-from-shading. Further, our stimuli rely on the light from above prior to create the impression of 3D shape from the shading pattern across the borders of the stimuli. However, it is unclear whether our results would generalise to 3D shaded stimuli that instead rely on shading gradients across the object (e.g., Aubuchon et al., 2025; Norman & Todd, 2025), or if a similar effect of lateralisation would also be present in scenes with naturalistic lighting. Finally, it is important to consider that viewing distance may have contributed to the effect of lateralisation observed in the current study, given that differences in rightward and leftward attentional biases have been observed at different viewing distances on the line bisection task (Britt et al., 2026). Therefore, it could be that the viewing distance employed in the current task is responsible for the left lateralisation of attention to 3D shape in the current study. However, we did not find an asymmetry of the N2pc component over the left hemisphere regardless of the target shape, suggesting that the task did not evoke a general left hemispheric dominance of attention. As such, we believe that viewing distance played a limited role in the results of the current study. Nevertheless, it would be beneficial for further research to consider viewing distance when assessing the lateralisation of 3D perception.

5. Conclusion

In conclusion, this study used lateralised ERPs as a measure of attentional resources necessary to process 3D and 2D shaded stimuli. Exploratory analysis revealed a polarity reversal of the N1pc component for 2D but not 3D targets, consistent with the idea of an early element of depth processing which guides attention to 3D shape. Our planned analysis found that a greater amplitude N2pc component was elicited by 3D compared to 2D stimuli, suggesting that top-down attention enhanced the representation of 3D targets to identify explicit 3D shape. However, this effect was only present over the left hemisphere, suggesting a dominance of the left hemisphere in the processing of 3D shape-from-shading. We suggest that this left lateralisation of 3D shape-from-shading reflects enhanced processing in the ventral visual pathway of the left hemisphere that is dependent on top-down attention to recover explicit 3D shape. Our findings here not only support the notion that top-down attention is necessary for the perception of explicit 3D shape-from-shading but also argues for a dominance of the left hemisphere in 3D shape processing.

CRediT authorship contribution statement

Ayelet Sapir: Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Joshua P. Matthews:** Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Debra L. Mills:** Writing – review & editing, Supervision, Resources, Methodology. **Paloma Marí-Beffa:** Writing – review & editing, Supervision, Investigation.

Ethics approval

This study was approved by the School of Psychology and Sports Science at Bangor University on 10/01/2024 prior to any data being collected (Ethics approval number: 2023–17317), and all procedures were conducted in accordance with relevant laws and institutional guidelines.

Declaration of Generative AI and AI-assisted technologies in the writing process

The author(s) did not use generative AI technologies for preparation of this work.

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.

Acknowledgements

This research was supported by Scholarship funding provided by Bangor University for postgraduate research.

Data availability

All materials and data for the study can be found on the open science framework: https://osf.io/vqg96/overview.

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