Title: Neural Correlates of Visual Object Detection: A High-Density EEG Based Effective Connectivity Study

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ABSTRACT

Detection of objects is pivotal for optimal functioning and survival, especially in potentially threatening environmental conditions. However, the neural mechanisms underlying this phenomenon of visual object detection remain elusive. A combination of novel visual object detection task, high-density electroencephalography (HD-EEG), and effective connectivity was used to decipher the causal interactions among cortical regions involved in the 'detection' of visual objects in healthy individuals (n=51). Significant ($P < 0.05$; t-stat threshold: 4.739; Medium effect) causal interactions were observed at two different time windows. At 300 ms to 400 ms post-stimulus, there was an attenuation in the flow of information from the right Brodmann area (BA) 25 to ipsilateral BA 40, potentially reflecting reduced interference from error processing and conflict monitoring and thereby increasing sensitivity for prompt detection of visual objects. Increased flow of information from left BA 9 to bilateral BAs 29 was noted at 350 ms to 450 ms, representing pre-frontal driven attentional signal guiding interpretation of the presence of visual objects. Additionally, enhanced connectivity from left BA 4 to contralateral BA 30 was observed at 350 ms to 450 ms indicating that enhanced integration of motor programs with visual processing contributes to the formation of coherent representations that facilitate interaction with visual objects in the external world.

Keywords: Brodmann areas, Cingulate cortex, Electroencephalography, Visual processing, Visual hallucinations

Introduction:

Accurate detection of visual objects is crucial for safe and efficient interaction with the environment. Evidence from longstanding research pertaining to visual objects has suggested that the ventral visual processing stream underlies object recognition (Gross, 1994; Mishkin et al., 1983; Orban, 2008; Ungerleider & Haxby, 1994). This involves the transmission of information from the occipito-temporal cortex to the anterior-inferior temporal cortex, continuing to the inferior frontal cortex (Kravitz et al., 2013; Ungerleider & Haxby, 1994). However, the alternate evidence have indicated that the object representations are not restricted to the ventral pathway alone but are also supported by the regions of the dorsal pathway (Bracci & Op de Beeck, 2016; Freud et al., 2016; Konen & Kastner, 2008). In addition, studies have revealed the contribution of other regions such as the pre-frontal and parietal cortex in visual object recognition (Bar et al., 2006; Dehaghani et al., 2022; Miyashita & Hayashi, 2000). Further, this phenomenon of visual object recognition is not just a single process but includes 'detection', 'categorization', and 'identification' as distinct components (de la Rosa et al., 2011; Grill-Spector & Kanwisher, 2005). It has been suggested that the presence of objects is detected in the background before being recognized with greater detail (de la Rosa et al., 2011; Nakayama et al., 1995). At times, mere detection of an object, rather than its detailed recognition, is crucial for swift and secure interaction with the surroundings. A growing set of studies has investigated the neural mechanisms that the brain employs to solve object recognition (DiCarlo et al., 2012; Grill-Spector et al., 1999; Grill-Spector & Malach, 2004; Kanwisher et al., 1996; Konen & Kastner, 2008; Kourtzi & Kanwisher, 2000; Logothetis & Sheinberg, 1996; Ungerleider & Haxby, 1994). Primate studies have suggested that the inferior temporal cortex is the site of neural organization essential visual object recognition (Dean, 1976; Eldridge et al., 2022; Gross, 1994; Tanaka, 1996). Positron emission tomography

(PET) studies in humans have shown activation of occipito-temporal regions during object recognition (Haxby et al., 1994; Köhler et al., 1995). Studies utilizing functional magnetic resonance imaging (fMRI) have identified functional connections among human brain regions responsive to visual stimuli such as faces, indicating a distinct processing stream along the ventral extra-striate pathway to the occipital face area and fusiform face area (Gschwind et al., 2012; Pyles et al., 2013). Intracranial electroencephalography studies have further demonstrated the visual object processing in the human medial temporal lobe and lateral occipital cortex(Qi et al., 2024; Vlcek et al., 2020). Magnetoencephalography has revealed the initial involvement of the inferior occipital, inferior temporal, and superior occipital gyrus followed by subsequent activity in the anterior inferior temporal gyrus and superior parietal gyrus during categorization which is a component process of visual object recognition(van de Nieuwenhuijzen et al., 2013). Besides this, the pre-frontal and parietal cortex have been demonstrated to be involved particularly in detecting the presence of objects (Das et al., 2007; Passingham & Lau, 2019; Sharifi et al., 2025). However, the causal interactions among cortical regions involved exclusively in the 'detection' component of object recognition have remained understudied which the current study aimed to address through a novel task of visual object detection.

Variability in low-level image properties such as spatial frequency can be a confounding factor in visual object detection task (Crouzet & Thorpe, 2011; Gaspar & Rousselet, 2009; Honey et al., 2008; van de Nieuwenhuijzen et al., 2013; Wichmann et al., 2006). This has been minimized by equalizing the low-level perceptual features of the images utilized in this study using the SHINE (spectrum, histogram, and intensity normalization and equalization) toolbox in MATLAB (Willenbockel et al., 2010). Further, the emotional stimulus is known to influence visual processing by inducing attentional bias mediated by the amygdala and interconnected pre-frontal areas

(Bendall et al., 2022; Eastwood et al., 2003; Pool et al., 2016; Pourtois et al., 2013). Images with neutral-valence (Bradley et al., 2008) obtained from International Affective Picture System (IAPS) (Lang et al., 2008) and Nencki Affective Picture System (NAPS) (Marchewka et al., 2014) were utilized in this study to mitigate this potential confounding effect on visual object detection. A novel task of visual object detection consisting of images with equalized properties and neutral emotional valence minimizes the confounding effects from emotional component and low-level image variability. The neural processing of visual objects has been shown to be achieved through multiple stages of transformations operating at a millisecond scale (DiCarlo et al., 2012; Gifford et al., 2022; Kirchner & Thorpe, 2006; Thorpe et al., 1996). To capture such rapid events, electroencephalography offering high temporal resolution due to the disproportionate decay of high-spatial frequencies during volume conduction from electrical sources in the brain to electrodes on the scalp was utilized in this study(A. K. Robinson et al., 2017). High-density electroencephalography (HD-EEG), which has been shown to effectively evaluate temporo-spatial aspects of visual processing of objects (Marino & Mantini, 2024; A. K. Robinson et al., 2017) that involve widespread brain regions extending from occipital to the frontal cortex (Barceló et al., 2000; Kravitz et al., 2013; Mishkin et al., 1983; Ungerleider & Haxby, 1994), was used in this current research. It was combined with the "effective connectivity" measure which evaluates the directional interactions among cortical regions (Friston, 1994; Nolte et al., 2008). Considering the framework outlined so far, the present exploratory study aimed to decipher the physiological causal interactions among cortical regions underlying the 'detection' of neutral valent visual objects using HD-EEG.

METHODS

Participants

Fifty-one healthy volunteers (33 Males; Mean age = 25.73 ± 4.39 years) participated in this study. All participants included in the study provided written informed consent before the procedure commenced. The procedures undertaken in this study complied with the latest revision of the Declaration of Helsinki for medical research involving human subjects and were approved by the Institutional Ethics Committee. All participants reported no past or present history of head trauma, neurological or psychiatric disorders, medical illnesses, or substance use disorders, and they had corrected visual acuity of 6/6. Participants were included if they reported sleeping at least 6.5 hours on either of the two previous nights. Those who had consumed tea, coffee, caffeinated drinks, alcohol, medication, or drugs within 6 hours before the experiment were excluded from the study.

Visual object detection task (VODT)

Eighteen images with neutral valence (Bradley et al., 2008) ranging from 4 to 6 (Mean valence: Male: 5.323±0.455, Female: 5.262±0.502) were chosen from International Affective Picture System (IAPS) (Lang et al., 2008) and Nencki Affective Picture System (NAPS) (Marchewka et al., 2014) and standardized. The images were resized (640 x 480 pixels) using Adobe Photoshop 2020 and the low-level perceptual features of the images were equalized with the SHINE (spectrum, histogram, and intensity normalization and equalization) toolbox in MATLAB (Willenbockel et al., 2010). E-Prime 2.0 software was used for scripting and administration of novel visual object detection task (VODT). Participants were seated comfortably in a dark, silent room. A 17-inch flat panel LCD monitor (Dell Professional P170S, refresh rate 60 Hz) was used for performing VODT. The stimuli were displayed on a computer screen which subtended a visual angle of 13° in the horizontal plane and 10° in the vertical plane. The VODT (Fig. 1) consisted of

26 distinct images, including 18 images featuring objects from four categories: human, animal, plants, and inanimate objects, along with 8 blank images. Each unique image was presented 6 times, resulting in a total of 156 trials, with the sequence of trials randomized for each participant. Before starting the task, participants were briefed on the procedure and instructed to keep their eyes fixed on the fixation point (symbol +) positioned in the center of the computer screen. Participants were instructed to indicate if each image included an object, by responding with key '1' for yes and key '2' for no on the response pad. Since the present study targets the 'detection' phase of visual object recognition, participants were instructed to respond if they could merely perceive the presence of an object rather than identifying its detailed characteristics. The uniform gray field with a fixation point (+) was viewed during the inter-stimulus interval.

EEG Data Acquisition

Before commencing the experiment, participants were provided with detailed instructions and conducted a practice session to acquaint themselves with the task. Data were acquired during baseline resting state with their ‘eyes open’ and during visual object ‘detection’ task using high-density (128 channel) HydroCel Geodesic Sensor Net (HCGSN) (Magstim EGI, Eugene, USA), Net Station (Version 5.4.2) and Net Amps 400 amplifier (Magstim EGI, Eugene, USA). Proprietary software Net Station with a sampling rate of 1 KHz and electrode impedances were kept below 50 kΩ. The vertex electrode (Cz) served as the recording reference.

EEG Data pre-processing

Data segmentation was carried out using Net Station software (Version 5.4.2). Data epochs of 1500 ms starting from 100 ms before and extending 1400 ms after stimulus presentation of visual object detection task trails with correct response were taken. Data epochs of 1500 ms of the ‘Eyes open’ condition were taken as a baseline for comparison. Subsequent pre-processing steps were done using ‘Automagic’ (Pedroni et al., 2019), an open-source MATLAB toolbox. EEG electrodes positioned on the outermost circumference placed over the skin of the face and neck (48, 49, 56, 63, 68, 73, 81, 88, 94, 99, 107, 113, and 119) were excluded from preprocessing. Bad channels were identified using the ‘PREP discard notch pipeline’, and refrained from filtering, as it has been shown to affect the temporal dynamics of electrophysiological signals (VanRullen, 2011; Yael et al., 2018). All the channels that were detected as bad channels were interpolated using the “spherical” interpolation method. Data were then re-referenced to a common average reference to minimize the effects due to reference site activity.

Source analysis

Source analysis was conducted to explore the brain regions engaged in the detection of visual objects using exact low-resolution brain electromagnetic tomography (eLORETA), an algorithm that solves the inverse problem by computing the smoothest of all possible distributions of current density (Pascual-Marqui, 2007; Pascual-Marqui et al., 2011). The probabilistic location of gray matter in the average MRI atlas of the Montreal Neurologic Institute (MNI) Atlas (Mazziotta et al., 2001) was used to constrain the location of 6239 source voxels. The source space was restricted to 6239 cortical voxels (5 mm^3 spatial resolution) that were parceled into 84 regions of interest (ROIs) and corresponding Brodmann areas.

Analysis of effective brain connectivity

Effective brain connectivity was assessed using the Phase Slope Index (PSI) (Nolte et al., 2008), which estimates both the direction and strength of information flow between the ROIs. PSI was chosen due to its insensitivity to volume conduction and its ability to detect only non-zero phase delays, enabling effective connectivity network estimation at the sensor level (Mahjoory et al., 2017; Nolte et al., 2008). Effective connectivity of ROIs was obtained in a time series of 100 ms moving window with 50% overlap (i.e., 50 ms). Connectivity matrices were then imported into LORETA software to carry out statistical analysis using SnPM (Statistical nonparametric mapping).

Statistical analysis and plotting of effective brain connectivity

“Connectivities or time-varying log spectra” in “Statistics” implemented in LORETA (Pascual-Marqui et al., 1994) was used to analyze the effective connectivity data. It gives a critical probability threshold for the actually observed t-values with correction for multiple comparisons across all voxels. For each SnPM randomization test, a total of 5000 permutations were used to determine the significance (Nichols & Holmes, 2001). Further, the localization of global, widespread correlations between the cortical voxel activity was assessed by applying the exceedance proportion test which assessed the significance of clusters of voxel activity based on its spatial extent and height threshold, obtaining clusters of supra-threshold voxels (Friston et al., 1990, 1991). BrainNet viewer (Xia et al., 2013), a network visualization tool for human brain connectomics, was utilized to illustrate the results of effective connectivity.

Results

The causal interactions were significantly different ($p < 0.05$) during the “visual object detection” when compared to the baseline condition i.e. “eyes open” (Fig. 2). Within the analyzed segment of 1500 ms, there was reduced flow information from the right Brodmann area 25 (Medial frontal gyrus, Subcallosal gyrus, and Anterior cingulate gyrus) to ipsilateral Brodmann area 40 (Inferior parietal lobule, Postcentral gyrus, and Supramarginal gyrus) at the 300 ms to 400 ms window of post-stimulus period. Whereas, at 350 ms to 450 ms window of post-stimulus period, increased flow of information from left Brodmann area 9 (Superior, Medial, Middle, and Inferior frontal gyrus and Precentral gyrus) to bilateral Brodmann areas 29 (Posterior cingulate gyrus); from left Brodmann area 4 (Precentral gyrus, Postcentral gyrus and Paracentral lobule) to contralateral Brodmann area 30 (Parahippocampal gyrus, Posterior cingulate gyrus and Cuneus) was observed.

Discussion

The current study attempted to elucidate the cortical causal interactions underlying the ‘detection’ of visual objects using a combination of HD-EEG and effective connectivity. Significant causal interactions were observed at various time points during visual object ‘detection’ compared to baseline. At the 300 ms to 400 ms window of the post-stimulus period, there was reduced connectivity from the right Brodmann area 25 to ipsilateral Brodmann area 40. At the 350 ms to 450 ms window of the post-stimulus period, there was an increased connectivity from left Brodmann area 9 to bilateral Brodmann areas 29; and from left Brodmann area 4 to contralateral Brodmann area 30 (Fig. 2).

Reduced connectivity from the right Brodmann area 25 (Anterior cingulate gyrus, Medial frontal gyrus, and Subcallosal gyrus) to ipsilateral Brodmann area 40 (Inferior parietal lobule, Postcentral gyrus, and Supramarginal gyrus)

Increased activation of both the anterior cingulate gyrus and right inferior parietal lobule encompassing the supramarginal gyrus have been found to be associated with error detection and correction (Garavan et al., 2002). Whereas the current study found reduced connectivity from the right anterior cingulate cortex to the ipsilateral inferior parietal lobule during visual object detection task. Detecting errors leads to a reduction in cognitive processing efficiency, which in turn hinders subsequent performance (Musco et al., 2023). Focusing on error detection diverts attention, negatively affecting task performance (Jentzsch & Dudschig, 2009; Musco et al., 2023; Notebaert et al., 2009). Therefore, decreased cortical interactions among error processing regions as observed in this study could reduce interference with the task, thus increasing the likelihood of detecting objects without being hindered by concerns about potential errors. Similarly, as the anterior cingulate gyrus is linked to conflict monitoring (Botvinick et al., 2004; Kerns et al., 2004), reducing its interaction could result in directing more focus on detecting the objects by reducing the cognitive burden of conflict about whether the object is actually present. Further, considering the association between the right medial frontal gyrus and response inhibition (Chambers et al., 2009; Garavan et al., 2002), reduced connectivity with this region could weaken the process of response inhibition, thereby allowing for more attempts to detect the presence of an object. In addition, reducing the connectivity with the post-central gyrus which is known for its role in somatosensory processing (Roux et al., 2018; Schott, 1993) could minimize the cognitive costs (Bullmore & Sporns, 2012) thereby aiding efficient performance of cognitive task such as object detection.

In summary, the decreased causal interactions among the above-mentioned fronto-parietal cortical regions reduce the interference from error processing and conflict monitoring, thereby maximizing the opportunities and optimizing the attempts for swift detection of visual objects.

Enhanced connectivity from left Brodmann area 9 (Superior, Medial, Middle, and Inferior frontal gyrus and Precentral gyrus) to bilateral Brodmann areas 29 (Posterior cingulate gyrus)

The pre-frontal and parietal cortex have been demonstrated to play a critical role in the detection of objects (Dehaene & Changeux, 2011; Markov et al., 2014). The literature suggests that the target-related information processing initiated in the pre-frontal area is then transferred to posterior brain areas during stimulus presentation (Karimi-Rouzbahani et al., 2019) to facilitate visual detection. In line with this, the current study observed enhanced connectivity from left frontal cortical regions to bilateral posterior cingulate gyrus during the detection of visual objects.

Pre-frontal cortex which lies at the top of hierarchical visual processing (Azuar et al., 2014) contains neurons that encode details of the visual stimulus (Mendoza-Halliday & Martinez-Trujillo, 2017) and its activation reflects the conscious awareness of visual objects (Passingham & Lau, 2019). The dorsal pre-frontal cortex is engaged in distinguishing whether an object is 'seen' or 'not seen' (Passingham & Lau, 2019) and the current study noticed the involvement of pre-frontal cortical regions when participants indicated detecting the visual object. Frontal brain areas contribute to generating the contents of visual perception (Libedinsky & Livingstone, 2011) and detecting the presence of visual objects (Sharifi et al., 2025). PFC integrates information from the external environment with stored internal representations (Miller, 2000; Vincent et al., 2008) and is also involved in the process of visual searching (Merten & Nieder, 2012; Thompson & Schall, 2000) which may facilitate visual object detection.

Further, visual detection depends critically on attention (Kanwisher & Wojciulik, 2000) and studies have shown that parts of PFC are active during attention (Baldauf & Desimone, 2014; Bressler et al., 2008). The superior frontal gyrus (Corbetta et al., 2008; Fox et al., 2006), middle frontal gyrus (Fan et al., 2005; Posner, 2012; Raz, 2004; Uddin et al., 2019; Vernet et al., 2014), Inferior frontal gyrus (Fan et al., 2005; Posner, 2012; Raz, 2004; Uddin et al., 2019), and Precentral gyrus (Fan et al., 2005; Posner, 2012; Raz, 2004; Uddin et al., 2019; Vernet et al., 2014) are implicated in attention and involvement of these areas observed in the current study during the detection of visual objects. While the left superior frontal gyrus has been found to be activated during orientation (du Boisgueheneuc et al., 2006) and monitoring of information (du Boisgueheneuc et al., 2006; Owen et al., 1996; Petrides, 2005), the left medial frontal gyrus is linked with perceptual decisions based on object-related information (Talati & Hirsch, 2005). Activity in the frontal eye field (FEF) cells, located in the middle frontal gyrus (Libedinsky & Livingstone, 2011; Thompson & Schall, 2000), has been recorded during visual processing, with the FEF contributing significantly to the deployment of top-down attention (Armstrong et al., 2006; Gregoriou et al., 2009a, 2009b).

Detecting a target object involves strategies in the brain that integrate external sensory-driven and internal task-driven mechanisms (Karimi-Rouzbahani et al., 2019) and the posterior cingulate cortex is involved in regulating the balance between internally and externally focused cognitive processes (Leech et al., 2011). Studies have demonstrated that the PCC is engaged in gathering extensive information, which is essential for responding to a rapidly changing environment (Hayden et al., 2008, 2009; Leech et al., 2011; Pearson et al., 2009, 2011). The process of detection requires integration of information from brain regions of diverse networks with distinct functions

(Leech et al., 2012) and the PCC plays a pivotal role in orchestrating this functional integration (Andrews-Hanna et al., 2014; Leech & Sharp, 2014).

The posterior cingulate cortex serves as a cortical hub (Hagmann et al., 2008) and has a significant functional connection to the PFC (Greicius et al., 2003). Lesions in the frontopolar cortex, located within the PFC, disrupt functional connectivity between the FPC and PCC, emphasizing their collaborative involvement in cognitive processes (Ainsworth et al., 2022). In support of this view, the present study found enhanced physiological communication between pre-frontal cortical regions and the posterior cingulate cortex during object detection. Frontal and parietal regions dynamically adjust their responses to selectively encode relevant information during visual processing (Duncan, 2001; Woolgar et al., 2015). Further, the increased connectivity between the posterior cingulate cortex and pre-frontal cortex is related to attention control (Sezer et al., 2022). The direction of visual attention has been associated with the parietal and frontal lobes, as patient studies indicate that damage in these brain regions leads to attentional impairments (Mesulam, 1981; Posner et al., 1984). Furthermore, single-unit studies demonstrate that many neurons in these areas exhibit stronger responses to attended stimuli compared to unattended ones (Kanwisher & Wojciulik, 2000; D. L. Robinson et al., 1978; Wurtz & Mohler, 1976). These studies (Mesulam, 1981; Posner et al., 1984; D. L. Robinson et al., 1978; Wurtz & Mohler, 1976) have uncovered a distributed network of higher-order areas in the frontal and parietal cortex suggesting their involvement in the generation and regulation of top-down attentional signals (Kanwisher & Wojciulik, 2000; Kastner & Ungerleider, 2000).

Attention and perception are so closely connected that it's difficult to distinguish which one drives the other (Holm et al., 2008; Ito et al., 2003; Pomplun et al., 1996). Attention amplifies the multi-voxel representation of visual information (Woolgar et al., 2015) and the significant findings from the single-unit studies have indicated that attention can modulate the gain of neural responses to visual stimuli (Beauchamp et al., 1997; Corbetta et al., 1990; Reynolds et al., 2000). Through an additive increase in the baseline firing rate of visual neurons that represent the attended stimulus, attention can increase neural activity by a constant amount independent of the strength of the stimulus (Kanwisher & Wojciulik, 2000; Paneri & Gregoriou, 2017). Additional evidence supports the significance of dorsal prefrontal and parietal cortices in target detection, with cell activity in these areas reflecting the level of confidence in detecting visual objects (Cortese et al., 2016; Kiani & Shadlen, 2009; Middlebrooks & Sommer, 2012; Passingham & Lau, 2019).

In summary, the current study emphasizes the interactive role of pre-frontal and posterior cingulate cortices resulting in attentional signals facilitating interpretation of the presence of visual objects.

Enhanced connectivity from left Brodmann area 4 (Precentral gyrus, Postcentral gyrus, and Paracentral lobule) to contralateral Brodmann area 30 (Parahippocampal gyrus, Posterior cingulate gyrus and Cuneus).

Apart from controlling voluntary movement (Lemon, 2008; Schott, 1993), motor areas, by virtue of its connections with cortical regions such as the cingulate area are involved in higher-order aspects of cognitive functions (Luppino & Rizzolatti, 2000). The precentral gyrus (Fan et al., 2005; Posner, 2012; Raz, 2004; Uddin et al., 2019) and postcentral gyrus (Balslev et al., 2013) are implicated in attention which can influence cognitive processing in extra-striate visual areas (Kanwisher & Wojciulik, 2000). While the cuneus is linked with basic and the higher order visual processing required for the orientation and direction of stimuli (Grill-Spector & Malach, 2004), the parahippocampal gyrus is further associated with visual processing (Levy et al., 2001). The engagement of cortical motor regions in visual processing could be essential for reflecting the potential motor acts afforded by the object (Maranesi et al., 2014). Object-specific response of the premotor cortex is likely to represent the neural activity associated with using the object (Grafton et al., 1997). The ability to respond to environmental stimuli through visual and motor coordination is vital for effective interaction and survival and the current study observed the interaction of motor areas with visual processing areas(Sepulcre, 2014). Integration of visual perception with motor programs produces coherent temporo-spatial representations that enable interaction with the external world (Sepulcre, 2014).

While the current study was focused on the physiological aspects of visual object detection, the alterations in the detection of visual objects have been reported across different physiological and pathological states such as visual hallucination (Lana-Peixoto, 2014; Teeple et al., 2009). This phenomenon can be experienced by healthy individuals (Lana-Peixoto, 2014) or by patients with ophthalmological diseases (ffytche, 2009), neurodegenerative disorders such as Parkinson's Disease (Fénelon et al., 2000), dementia with Lewy bodies (O'Brien et al., 2020), Alzheimer's disease (O'Brien et al., 2020) as well as with psychiatric disorders such as Schizophrenia (Silverstein & Lai, 2021). Despite numerous proposed mechanisms to explain the pathophysiology of visual hallucinations (Kumar et al., 2009; O'Brien et al., 2020), a specific mechanism remains elusive. Recent findings suggest that the alterations in both top-down and bottom-up effective connectivity are linked to visual hallucinations in Parkinson's disease (Thomas et al., 2022). Observations in Parkinson's disease patients with visual hallucinations revealed a decrease in bottom-up effective connectivity from the lateral geniculate nucleus to the primary visual cortex and increased top-down effective connectivity from the left pre-frontal cortex to both the primary visual cortex and the medial thalamus (Thomas et al., 2022). Significant lower functional connectivity in frontal, paracentral regions, and occipital brain areas which are related to attention and visual perception have been observed in patients with visual hallucinations (Hepp et al., 2017). The current study highlights the role of enhanced connectivity from prefrontal and paracentral to the posterior cingulate cortex and visual areas in healthy individuals for detecting visual objects. The pathophysiological mechanisms underlying visual hallucinations may involve reduced neural network efficiency, potentially disrupting attention and visual processing (Hepp et al., 2017). Future research on the effective connectivity involved in visual object detection in patients with neuropsychiatric disorders could advance the understanding of the neural mechanisms involved in visual object detection across various physiological and pathological states.

Summary and Conclusion

The current study concentrated on exploring the neural mechanisms underlying the detection of visual objects by analyzing causal cortical interactions utilizing EEG effective connectivity. The initial reduction in interactions between the right fronto-parietal cortical regions reduces the interference from error processing and conflict monitoring, thereby maximizing the opportunities for prompt detection of visual objects. Subsequent enhanced interaction of left pre-frontal areas with bilateral posterior cingulate cortices facilitates attention and functional integration enabling awareness of the presence of objects. In addition, the strengthened integration of somato-motor and visual processing regions could further strengthen vigilance to detect visual objects efficiently. While other researchers have reported lower functional connectivity in frontal, paracentral regions, and occipital regions in patients with visual hallucinations, the present study highlights the enhanced connectivity among these similar regions in healthy individuals. By analyzing the effective connectivity involved in visual object detection in patients with neuropsychiatric disorders, future research could provide valuable insights into the pathophysiological mechanisms underlying phenomena such as visual hallucinations.

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Author contributions

Conceptualization: YN Arun, Suriya Prakash Muthukrishnan; Project administration: YN Arun, Suriya Prakash Muthukrishnan; Supervision: Suriya Prakash Muthukrishnan; Investigation: YN Arun, Madhu Priya, Sudhashekhar Kumar; Methodology: YN Arun, Suriya Prakash Muthukrishnan, Sunaina Soni, Prashant Tayade, Simran Kaur, Ratna Sharma; Data curation: YN Arun, Suriya Prakash Muthukrishnan; Statistical analysis: YN Arun, Suriya Prakash Muthukrishnan, Sunaina Soni; Writing—manuscript preparation: YN Arun; Writing—reviewing and editing: YN Arun, Suriya Prakash Muthukrishnan

Ethics declarations

This study was approved by the Institutional Ethics Committee. Written informed consent was obtained from all the participants prior to their involvement in the study.

Consent for publication

All participants provided written informed consent.

Competing interests

The authors declare no competing interests.

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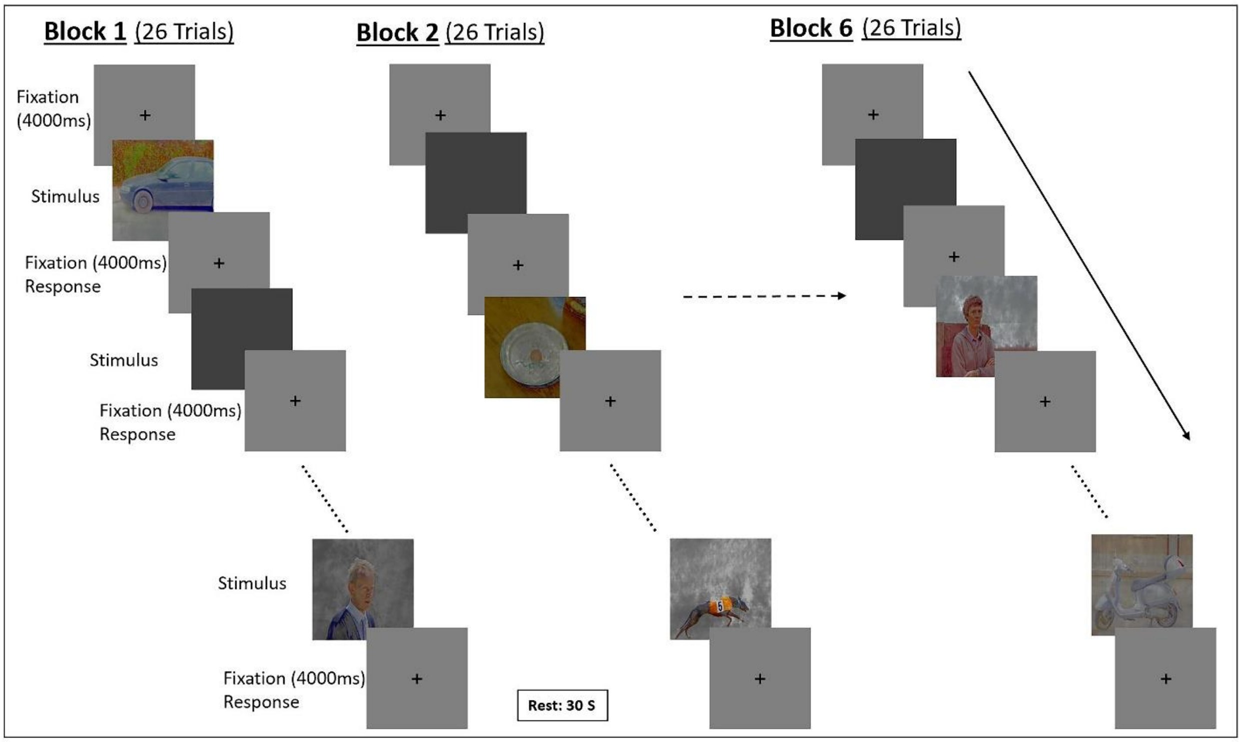

Fig. 1. Visual object detection task (VODT). The VODT consisted of six blocks and each block had twenty-six trials. This task contained 26 distinct images, including 18 images featuring objects from four categories (human, animal, plants, and inanimate objects) along with 8 blank images. Each unique image was presented 6 times, resulting in a total of 156 trials. The stimulus was presented after a brief presentation of the fixation point. Each stimulus was presented with a gap of 4 seconds. A uniform gray field with a fixation point (+) was viewed during the inter-stimulus interval during which participants made their responses. The inter-block interval was 30 seconds. The sequence of blocks and trials was randomized for each participant.

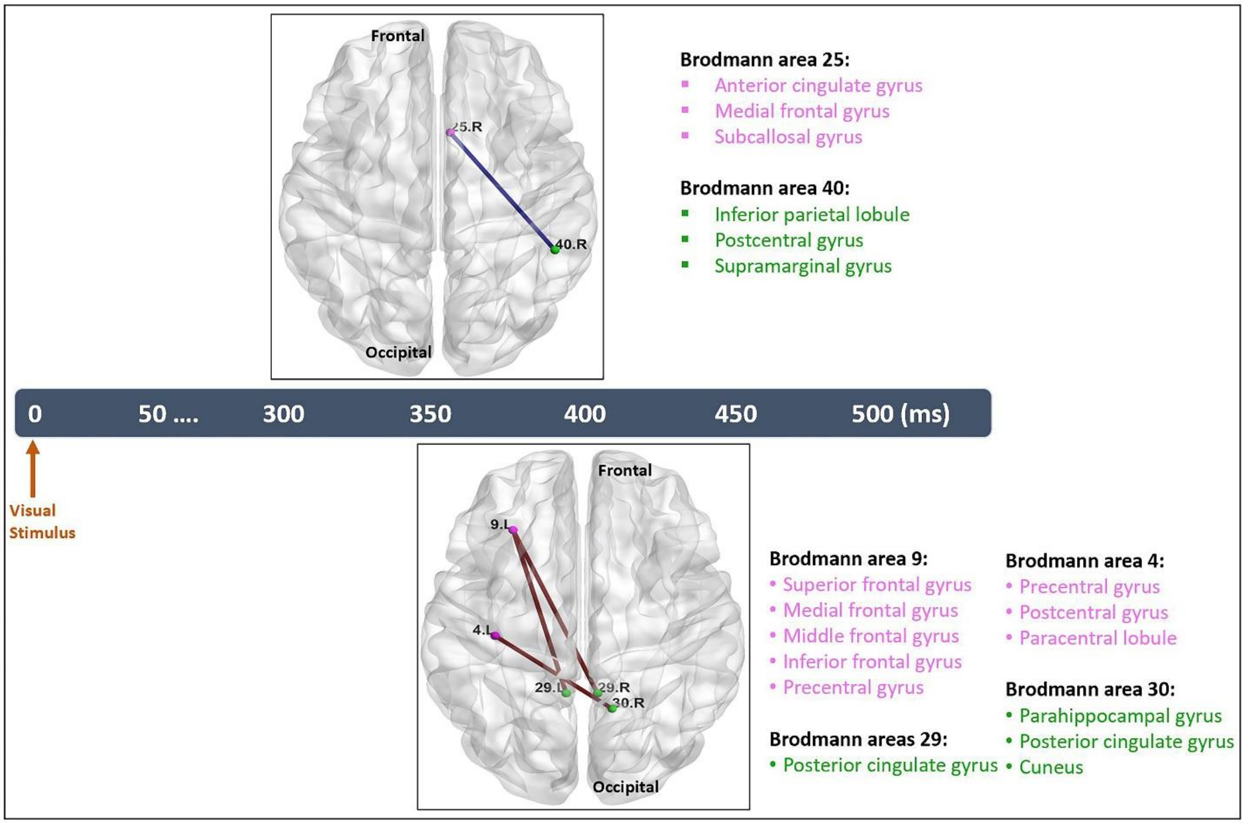

Fig. 2. Effective brain connectivity during visual object detection.

The nodes depicted in pink and green represent the brain regions that are sending and receiving the information, respectively. The nodes in light blue represent the brain regions that send as well as receive the receive information. The edges depicted in brown and blue represent the increased and decreased connectivity respectively. $P < 0.05$; t-stat threshold: 4.739; medium effect. R: Right cerebral hemisphere. L: Left cerebral hemisphere. The numbers correspond to the Brodmann area.