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Review article

Integrative parietal cortex processes: Neurological and psychiatric aspects

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ABSTRACT

For many decades the parietal cortex (PC) has been considered the key area in tasks which involve the integration of different stimuli. PC is fundamental to determine spatial sense, information navigation and integration, and is involved in several aspects of the complex motor repertoire and in neurological and psychiatric disorders. In this review, we focus on seven different aspects of PC: (i) neuroanatomy of the parietal cortex; (ii) sensory motor integration processes; iii) hand movement control: reaching, grasping, and pointing; (iv) saccadic eye movements; (v) movement observation; (vi) neurological aspects: ataxia, autism and Parkinson's disease; and (vii) psychiatric aspects: schizophrenia, bipolar disorder and depression. Among these, we related the perspectives which involve the functions of the parietal cortex and mirror neurons and that seem to play a fundamental role in action prediction, planning, observation and execution. Furthermore, we focused on the relationship between posterior parietal cortex (PPC) and hand-guided movements. For this review, we conducted an academic paper search which fulfilled the objective of the study. We conclude that the PC has great participation in different motor functions and neurological/psychiatric disorders.

Contents

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1. Introduction

The parietal cortex (PC), which in the past was considered part of the 'associative cortex', integrates information from different sensory sources [1]. Tracts from two or more sensory systems are integrated by the posterior parietal cortex (PPC) and this multimodal association area is responsible for some types of perceptions, such as space dimension and action guiding. Neuroanatomically speaking, the parietal cortex is a part of the brain located above the occipital lobe and behind the frontal lobe [2]. The parietal lobe includes the PPC as well as the dorsal stream of the visual system; thus, this cortex region can map objects perceived visually into body position coordinates [3]. Several experiments with primates have established a link between different parietal areas and a particular type of cognitive motor control [4]. The intraparietal sulcus, for example, has been associated with saccadic eye movement and attention processes [5]. Differently, the intra-occipital parietal junction and the medial-occipital parietal junction are related to movement execution [6]. Therefore, the parietal cortex participates in several aspects of motor action, since early object identification and selection of the best parameter for the proper action, until the final stage of executing it precisely. Considering this, the present review focuses on different aspects of the parietal cortex: (i) neuroanatomy of the parietal cortex; (ii) sensory motor integration processes; (iii) hand movement control: reaching, grasping, and pointing; (iv) saccadic eye movements; (v) movement observation, (vi) neurological aspects: ataxia, autism and Parkinson's disease; and (vii) psychiatric aspects: schizophrenia, bipolar disorder and depression. In order to answer these questions, we developed a strategy for searching studies in the main databases. The computer-supported search used the following databases: Scielo, Pubmed/Medline, ISI Web of Knowledge, PsycInfo and Cochrane Library. The search term parietal cortex was associated with: neuroanatomy, saccadic eye movement, sensory motor integration, reaching, grasping, pointing, ataxia, autism, Parkinson's disease, schizophrenia, bipolar disorder and depression. In addition, we included all report reviews, meta-analyses and controlled randomized clinical and open label trials. Thus, the aim of this review was to extract relevant information supporting the idea that the parietal area is a key element to understand how the central nervous system (CNS) is able to code different motor and sensory features in healthy and pathological instances.

2. Methodology

We conducted a search focusing on articles written in English from 1980 to the present day (i.e., thirty three years); only researches conducted with people and case-report or original articles were included. Thus, for this integrative review we employed the following search terms: neuroanatomy, sensory motor integration, reaching, grasping, pointing, saccade eye movement, movement observation, sensory–motor transformations, stroke, ataxia, autism, Parkinson's disease, schizophrenia, bipolar disorder and depression. In our research we combined the term "parietal areas" with the afore-mentioned terms and we only selected the articles that reported the parietal areas as search term. The results were then manually reviewed and the articles were considered for analysis; their relevance was determined by our consensus and by overall manuscript quality.

3. Results

We selected 35 articles with the combination of the terms "parietal areas" and "neuroanatomy"; 14 articles with "parietal areas" and "sensory motor integration"; 12 articles with "parietal areas" and "reaching, grasping, pointing"; 18 articles with "parietal areas" and "saccade eye movement", 33 articles with "parietal areas", and "movement observation and sensory–motor transformations"; 69 articles with "parietal areas" and "stroke, ataxia, autism and Parkinson's disease", 59 articles with "parietal areas" and "schizophrenia, bipolar disorder and depression". After this selection, we used 164 articles which fulfilled the objective of the study.

3.1. Neuroanatomy of the parietal cortex

The parietal cortex is an associative structure fundamental for sensorimotor integration processes; its sub-areas are responsible for different functions involved in sensory processing, memory, attention and movement anticipation [7,8]. It is located behind the frontal lobe and above the occipital lobe. The primary and secondary somatosensory cortices SI and SII (Brodmann areas 1, 2, 3 and 5) are found immediately behind the central sulcus, and between this and the posterior parietal cortex (see Fig. 1). The primary somatosensory cortex (SI), located in the postcentral gyrus, is the main sensory receptive area for the sense of touch, well known as the sensory homunculus, the space where the brain represents the body [9] (see Fig. 1). It is important to note that visual stimuli that imply touch have also been observed to activate the primary somatosensory cortex [10]. Secondary somatosensory cortex (SII), firstly described by Adrian as a second cortical representation of the cat's feet [11] is located in humans in the parietal operculum. Maps of the body surface in somatosensory cortex are highly plastic; distinct patterns of sensory use or disuse are continually reconfigured altering the homuncular maps [12,13].

The PPC has sub-divisions that are addressed in different ways. At first, the intra-parietal sulcus divides the PPC in superior (SPL) and inferior parietal lobules (IPL) (see Fig. 2). The intra-parietal sulcus is divided into angular gyrus, supramarginal gyrus and the edge of the superior temporal gyrus, known as temporo-parietal junction. In turn, the angular gyrus, which corresponds to Brodmann area 39, is divided into anterior and posterior regions, while the supramarginal gyrus corresponds to Brodmann area 40 and is subdivided in at least five areas [14,15] (see Fig. 1). The PPC is connected to the primary visual cortex, a path well known as 'the dorsal stream' of visual information, an occipito-parietal network dedicated to the processing of spatial information: the 'where' pathway [16,17]. Notwithstanding, in spite of sub-regions in the human SPL and intra-parietal sulcus contributing to spatial functions, there are evidences that the human IPL fits easily into either the dorsal or ventral streams (the latter being responsible for object identification, the 'what' pathway) [17,18]. The authors suggest that the IPL is part of a flexible system that alternates between these two modes of operation, according to current behavioral demands. Indeed, damage to the right IPL contributes to hemineglect, a syndrome characterized by lack of awareness of one side of the body and space that follows lesions to this region [17]. The angular and supramarginal gyri have a fundamental role in reading and writing. Transposition of Japanese

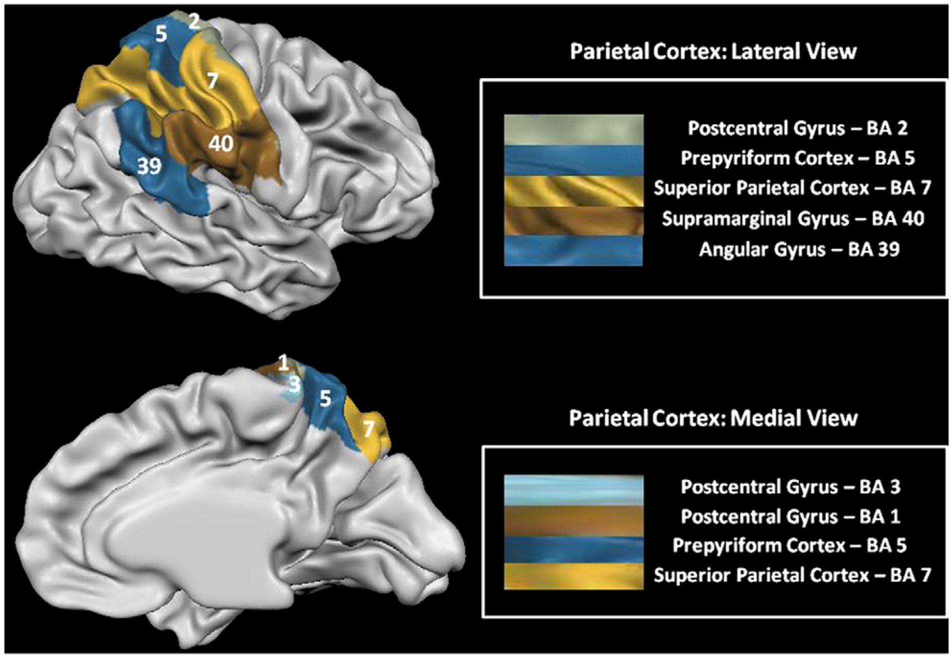

Fig. 1. Parietal structures and Brodman areas.

syllabogram characters in reading have been associated to disrupted sequential phonological processing from the angular and lateral occipital gyri to the supramarginal gyrus [19].

The second approach divides the PPC into lateral and medial segments, where the latter include mainly the precuneus (see Fig. 2). Consistent evidence indicates that this structure is directly involved in face perception [20]. The lateral parietal cortex has direct connections with the dorsal lateral prefrontal cortex, temporal cortex and medial parietal regions, as well as reciprocal connections with the hippocampus, parahippocampus and medial regions of the temporal lobe [21,22,23,24–26]. The parietofrontal connections mediate the transformation of visual information into action. Reaching, grasping and eye movements are guided by the caudal SPL and the intra-parietal sulcus, which are linked to agranular frontal cortex and frontal eye fields [27,28]. The neural mechanisms underlying attentional control in the frontoparietal network remain unclear. Some studies support a hemispatial theory emphasizing dominance of the right hemisphere; others support an interhemispheric competition theory [29]. A lower right-sided parietal activity had been associated with larger attentional control [30]; electroencephalographic (EEG) data showed that

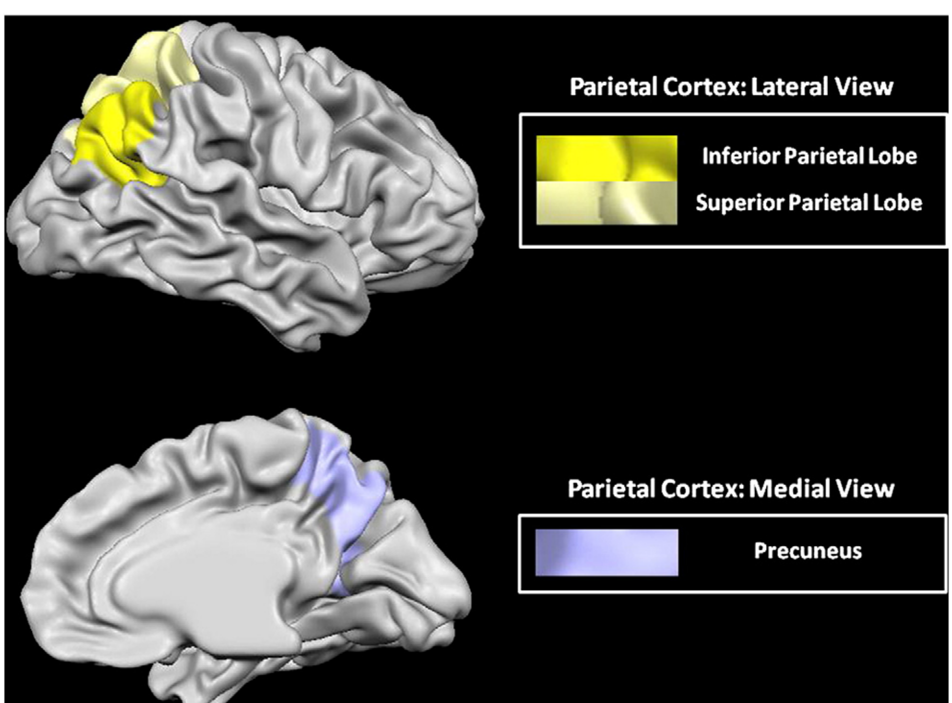

Fig. 2. Medial and lateral view of the parietal cortex.

differentiation between affective and cognitive conditions occurs in the right hemisphere, although the level of activation during emotional stimulation was high in the left hemisphere [31].

The third approach subdivides the PPC into dorsal and ventral parietal cortices. According to the authors, the dorsal parietal cortex consists of the lateral cortex, bordered by intra-parietal sulcus and superior parietal lobule, as well as the precuneus, and corresponds to Brodmann area 7 (see Figs. 1 and 2). In contrast, the ventral parietal cortex covers the angular gyrus and the supramarginal gyrus, corresponding to Brodmann areas 39 and 40 [8] (see Fig. 1). A functional magnetic resonance imaging (fMRI) analysis indicates a connection between the hippocampus and ventral parietal cortex, which can support theoretical currents arguing that the ventral parietal cortex processes memory information in the same way that it processes sensory stimuli [32]. Additionally, the ventral parietal cortex could be roughly equivalent to the inferior parietal lobule, and the dorsal parietal cortex could be associated with the superior parietal lobule.

Recent studies suggest the existence of neural connections involving the inferior parietal lobule and other brain areas such as the frontal and temporal cortices [33]. More precisely, an fMRI study showed a significant connection among the angular gyrus, basal ganglia and dorsolateral prefrontal cortex, while the supramarginal gyrus is connected with the hippocampus and the posterior cingulate. According to a model based on monkey brain mapping, and also applied to humans, the superior parietal lobule is part of a circuit that controls immediate actions, while the inferior parietal lobule is part of a system responsible for action understanding and spatial perception [34]. These particularities received support from other studies suggesting distinct inferior parietal lobule functions in each hemisphere. In particular, the right inferior parietal lobule detects new remarkable events in the environment and keeps the focus on the task goal, while the left inferior parietal lobule plays a role, yet little known, in the sustaining of limbs [35–44].

Some authors were more concise when describing the location of subareas, and suggest that the intra-parietal sulcus has four distinct sensory and motor regions. The ventral region is located in the posterior occipital part of the inferior parietal sulcus; the second region is at the confluence of the occipital and intra-parietal sulcus with the parieto-occipital sulcus. The third and fourth regions are located more dorsally in the cortex, at the parietal or horizontal segment of the intra-parietal sulcus, and so-called dorsomedial and anterior intra-parietal sulcus; the latter is located close to the junction with the post-central sulcus. The ventral intra-parietal sulcus is also referred to as intra-parietal sulcus; the anterior dorso-lateral intra-parietal sulcus is quoted as intra-parietal sulcus in other studies. The distinction of the sub-areas location is minimal and difficult to sustain due to image resolution divergences in the studies, but is confirmed by other authors [45–52].

3.2. Sensory motor integration processes

Considering a relatively simple task, such as using one finger to press a switch; although this action appears to require previous experience regarding hand position relative to target location, people use either hand to perform it, while this does not occur in tasks that require greater skills and spatial planning. This brings up important issues for understanding the functional aspects of sensory information acquisition, its associations and automatic execution of behavioral and motor response. Neurophysiologically, the brain integrates visual, proprioceptive and somesthetic inputs into spatial and sensorimotor representations related to the environment, in order to produce an appropriate motor response [53–55]. This process does not occur in specific areas, but rather through integration of sensory modalities [55]. In particular, the parietal cortex has been associated with spatial perception [56], spatial attention [42], representation, retention of sensory information, and priming memory [8]. Priming is a type of implicit memory related to the first representation of the stimulus in the brain [57].

Spatially, motor behavior requires that the nervous system extract the sensory information from the current or future body part positions and, at the same time, distinguish the peripheral sensory feedback according to the modifications in the environment [58,59]. In addition, the PPC is actively involved in the planning of "reaching" movements [60], visual–motor integration, and decision-making in terms of motor actions, i.e., action selection and movement preparation [61–63]. Thus, the parietal cortex must be involved so that the movements are well executed [64].

3.3. Hand movement control: reaching, grasping and pointing

Object interaction in the environment using hand-guided movements such as grasping, pointing and reaching depends on several parameters [65]. Our sensory inputs organs, e.g., vision and proprioceptive receptors, obtain essential information about object characteristics: shape, color, motion and others. Thus, through the sensorimotor integration process, this sensory information is transformed into motor data. This process promotes our ability to adapt motor actions or create new ones according to environmental demands [66]. Diverse studies using different kinds of models demonstrated a major role of the PPC in the performance of these movements. In a drug experiment, Gallese et al. [67] used microinjections of Muscimol to reversibly inactivate parts of the anterior intra-parietal area (AIP) of a monkey. The animal was trained to grasp different kinds of objects, and the inactivation generated a deficit in the hand. In addition, Gardner et al. [68] recorded the firing rate of 128 neurons in macaque monkey areas 5 and 7b (AIP of PPC) during a grasp-and-lift task. The highest neuron firing rates were observed during the initial three stages: approach, contact and grasp. Together, the results of these investigations demonstrate the role of macaque PPC during initial stages where sensory data needs to be transformed into motor commands for the production of skilled reach and grasp movements.

Furthermore, the use of neuroimaging devices and cortical stimulation techniques, e.g., fMRI and transcranial magnetic stimulation (TMS) make possible the investigation of human PPC during hand-guided movements. This allowed researchers to determine homologies between human and macaque cortical regions and also to identify the specialization of parietal areas for each kind of movement [69]. In an fMRI study, Chapman et al. [70] developed a pneumatic apparatus that was designed to investigate the reach-to-grasp task where the number of potential targets and their position varied. In order to analyze the neural correlates of visuomotor coordination, predictable and unpredictable target locations were compared under five conditions, three of which were related to the number of stimuli (three, two or one stimuli) and two conditions were based on the number of possible locations (one or three possible locations). The authors concluded that different parietal areas play a specific role during visuomotor coordination and that the left superior parietal lobule activation might reflect a spatial shifting mechanism to direct the processing focus to the selected stimulus. The increase of left parieto-occipital activity has been associated with higher demands of selection and motor planning. At last, the right intra-parietal sulcus could play a role in the identification of the object during less automatic tasks. Moreover, Filimon et al. [69] investigated cortical representations for reaching, with or without visual feedback from the moving hand. The subjects were instructed to maintain central fixation and reach to three targets in the periphery, horizontally located below the fixation point. The fMRI results demonstrated the activation of precuneus, medial, anterior intra-parietal and superior parietal cortex during both visual and non-visual reaching (See Figs. 1 and 2). This supports the idea that humans have multiple parietal reach regions and cortical networks for reaching that activate specifically for each sensory condition.

Besides this observation, a series of studies demonstrated that TMS applied on the anterior intra-parietal sulcus (aIPS) impairs grasping behavior [71–73]. In a virtual lesion experiment, Tunik et al. [71] showed that TMS applied 65 ms after balance disruption elicited deficits in the grip movement fine control. The task consisted of two sessions with the grasp movement executed in different positions. Under the first condition (unperturbed) the subjects had to grasp an object that was oriented 180° horizontally and under the second condition (perturbed), the object was oriented 90° vertically; they used the pincer-grasp (using the index finger and the thumb) under both conditions. They observed that the adaptation deficiencies generated by TMS disruption are goal dependent rather than effect related. This finding showed that aIPS plays an important role for dynamic control and error detection of reach-to-grasp actions. Moreover, Rice et al. [73] applied TMS on anterior, middle and caudal IPS during a task in which the individuals pressed a start button with the index finger when four different rectangular targets appeared on a monitor; two of them were moving targets (perturbation) and two of them were fixed (no perturbation). For this study, the visual feedback was controlled by liquid crystal shutter glasses, which were programmed to open for 200 ms at the start of each trial, and remained opaque between each trial. The task under no perturbation allowed evaluating IPS contributions for planning and execution. TMS was applied during the viewing period and on execution phase when object was visualized. However, the task executed under perturbation sought to analyze IPS involvement during error detection or correction. The results demonstrated that the aIPS plays an essential role during online control of grasping by integrating sensory and motor components.

Furthermore, Rice et al. [72] developed another study without the perturbed condition contributing to the role of the aIPS on reach-to-grasp movements. This study was composed by six females and three males that were instructed to grasp with left and right hands. The start button activated a device with 4 different targets. The subjects positioned at 57 cm from the target had to grasp an object when it appeared oriented vertically. The TMS was delivered in double pulses at left aIPS (LaIPS) and right aIPS (RaIPS) at the beginning of the reach-to-grasp movement and 100 ms after the first movement. The intensity of the stimulation on each hemisphere was 110% of the motor threshold. They concluded that the left aIPS disruption impaired grasping with the left hand and right aIPS disruption impaired grasping with only the right hand. They suggested that the contralateral hemisphere plays a dominant role in online control of grasping movements.

3.4. Saccadic eye movement (SEM)

The preparation and execution of saccadic eye movement (SEM) require visual capture and elaboration of spatial maps related to the visual information. The parietal cortex is widely studied for its involvement in SEM control, especially on the onset of the movement [74,75]. This area is connected with other regions that contribute to saccade control, such as superior colliculus and frontal eye field [76–78]. Furthermore, this cortical region has an important role in visuospatial attention processing, first because of its involvement in mental representation of visual stimuli, and then due to its participation in the transforming of sensorial stimuli into a motor command. In particular, neural assemblies located in the PPC that respond to visual stimuli fire more intensely depending on the SEM target [79]. Simon et al. [80] observed that individuals with PPC damage present an increase in saccade latency and some errors in target precision. In addition, Kapoula et al. [81] demonstrated a difference between the left and right PPC in saccade onset, using TMS. The right parietal cortex was involved in the process of disengagement from one point of the saccade, while the left parietal cortex participated in eye movement, through mechanisms of spatial selection, in order to locate a new target [72,79].

A recent study in primates investigated neural mechanisms during an association task between visual stimuli (face or place) and different actions (eye or hand movement). The findings demonstrated that PPC activity reflects the integration between sensorial information and a specific motor response [82]. This region did not respond to sensorial stimuli per se, but to the integration between the stimuli and the action required. In other words, the visual stimulus identification and the SEM establish different patterns of functioning in the parietal cortex [78].

Studies of patients with parieto-occipital junction lesion have pointed to the involvement of this area in a set of visuoperceptual skills, such as the visual identification of objects in visual search and tracking in motion perception and direction of eye toward the target [83,84]. Moreover, this region is involved in sensory integration, specifically eye–hand coordination [85,86]. Investigation of this area did not verify a hemispheric specialization during tasks involving target localization and SEM direction. Quinlan and Culham [87] investigated the organization of retinotopic information in cortical areas and the relation of these areas with visual control. They used fMRI to examine activation in the parieto-occipital area as a function of the stimulus distance: near (13 to 17 cm), medium (33 to 43 cm) and far (73 to 95 cm). The parieto-occipital junction demonstrated greater activation during the stimulus presentation in the 'near' distance, which indicates a more intense participation of this region in the processing of closer targets. One may expect an engagement of parieto-occipital junction in the processing of distant stimuli, especially when the participant is required to follow the target with the eyes, which indicates an involvement of this region in spatial perception of movement [88,89].

3.5. Movement observation: parietal areas and sensory–motor transformations

The ability to generate internal representations of motor actions is part of the cortical motor function; individual motivation combined with external factors determines whether these representations will be converted into real actions [90]. Complex sensory–motor transformations occur within the parietal cortex and motor areas [5,91–93]; among these changes, we highlight the transformation of an observed action into an objective one. Thus, the motor areas have a matching mechanism where observed activities relate to an internal representation of that motor action, i.e., a mirror mechanism. Finally, motor areas are involved in decision-making processes leading to the initiation of an effective motor act [94–97].

EEG activity and readiness potential (RP) were observed from individuals with selective lesions in the inferior parietal lobe (IPL) when exposed to a video showing a person grasping a colored object. Specifically, three groups were compared: parietal and ventral premotor cortex-lesioned patients and neurologically healthy subjects. The brain lesions were based on photographs of T1 and T2-weighted magnetic resonance imaging (MRI) scans. The object color was used for specifying the different motor actions which the subject had to perform; for example, when the object was green, the subject should grasp it, however when the object was red, he/she should remain still. The results demonstrated that neurologically healthy individuals and premotor patients exhibit a significant RP prior to the observed action, although no such RP is seen in patients with parietal lesions. The findings also showed that parietal cortex damage changes the ability to regulate the early planning phases. The researchers believe that the parietal cortex during action observation does not only or essentially reflect a mirroring process, but is also associated with an anticipatory process, which arises through previous learning [98].

Moreover, inferior parietal lobe (IPL) and the ventral premotor cortex (VPC), as well as the caudal part of the inferior frontal gyrus (IFG) are activated by observation or motor imagery. Imagination and observation may promote motor action execution through the stimulation of an internal model. Thus, internal model's activation helps to consolidate sensory–motor representation and it is used when individuals need to learn or (re) learn motor functions. Action observation and motor imagery increase the excitability of the corticospinal tract. Due to the complexity of motor imitation itself, its neural encoding joins a widespread network with the participation of different brain regions. Several experiments have used this technique to improve motor execution of stroke patients. For instance, eight ischemic stroke patients with moderate middle cerebral artery dysfunction and with chronic motor deficit of the upper extremity participated in the experiment. The findings showed a significant enhancement of motor functions during a 4-week treatment, when compared to the control group. Moreover, the fMRI showed significant increase in activity in the bilateral ventral premotor cortex (PMv), bilateral superior temporal gyrus, the supplementary motor area (SMA), the contralateral supramarginal gyrus and inferior parietal region (see Figs. 1 and 2) both during the task and object manipulation, both before and after therapy [99].

3.6. Neurological aspects: stroke, ataxia, autism and Parkinson's disease

For many years now, several experiments have examined the relationship between mirror neurons and different pathologies, such as: stroke, ataxia, autism and Parkinson's disease. We have decided to review studies about this topic because of its importance in the possible future treatment intervention. The parietal region seems to play a fundamental role in action prediction, planning, observation and execution. Experiments using patient samples showed that parietal injury on these individuals impairs their capability to mimic or understand and observe actions. Moreover, these individuals have problems in monitoring initial stages of their own movement planning.

3.6.1. Stroke: PPC and critical cortical node in the sensorimotor system

Various cerebral diseases cause functional changes in cortical excitability [3,100]. Particularly, in the parietal cortex there is a disturbance in the sensory integration process, impairing the implementation of motor acts [101,102]. Thus, the brain, in order to repair physical function, strategically promotes the reorganization of areas adjacent to the lesion site [101]. This was observed in a study using fMRI in hemiparetic stroke patients; passive hand movement was able to promote activation of the primary motor area and the contralesional PPC, indicating that proprioceptive input to the affected hemisphere can trigger activation in the contralateral somatosensory cortex [103–105].

Patients after stroke commonly stop using the affected limb in daily activities. This behavior undermines the recovery of motion and causes the “learned nonuse”. The constraint-induced movement therapy (CIMT) consists in restricting the movement of the unaffected limb and conducting extensive training of the affected limb in a variety of tasks [100,106,107]. This technique has shown favorable cortical reorganization and motor recovery after stroke [107]. The fMRI was used to identify whether these specific plastic changes were related with CIMT. The results indicated significant improvement in motor and functional properties of the affected limb through the Fugl-Meyer scale and motor activity log, and fMRI showed different patterns of cortical changes. Specifically, CIMT caused increased activation of the patients' cerebral hemispheres, in particular of the contralesional hemisphere during movement of the affected and unaffected hands. On the other side, the patients who received traditional rehabilitation showed decreased activation in the primary sensory motor cortex in the ipsilesional hemisphere during task performance with the affected hand [106].

3.6.2. Neurodevelopmental disorders

Autism disorders can range from specific serious social losses associated with severe mental retardation (Kanner Syndrome) to moderate losses, featuring normal or near normal intelligence (Asperger Syndrome). In addition, there are more subtle social deficits, such as those seen in children with attention, motor control and perception deficits [108]. Thus, the term Pervasive Developmental Disorder (PDD) was questioned for neurodevelopment disorders, due to the fact that continuum disorders are not affecting all functions on all levels (biological, cognitive, behavioral and social adaptation). Thus, we need to discontinue the PDD categorical classification, and emphasize a more dimensional view, therefore inserting the category of Autistic Spectrum Disorder (ASD) [109].

Thus, the autism is a syndrome which appears early on the developmental stage, essentially characterized by affected environment/social relations and communication, and by restricted, repetitive or stereotyped behavior. The syndrome affects the child information processing system at a very early age. Several results showed that the three main stages during the information processing are altered in individuals with autism syndrome. P300 wave is an event related potential (ERP) component elicited in the process of decision making. The wave's peak is typically measured most strongly by the electrodes covering the parietal lobe. The magnitude, topography and timing of this signal are regularly used as metrics of cognitive function in decision making processes. P300 amplitude affects attentional reserve allocation during discernment, the component elicited during perception of known and unknown faces should indicate familiarity processing. For example, P300 amplitude in healthy children was larger during familiar face perception than during unfamiliar face perception. However, there was no evidence of familiarity effect in children with autism syndrome disorder (ASD) [110]. Moreover, current investigations have shown that there are specific irregularities in early processing that are probably related to sensorial perception. ERP amplitudes in reaction to visual stimuli, measured above the occipital cortex, are reported to be abnormally small in patients with PDD and the abnormal visual processing is possibly associated with the spatial visual frequency content of stimuli. It is believed that individuals with PDD present abnormal activation of visual pathways dedicated to the processing of high and low spatial frequencies [111]. In another investigation, ASD children, attention deficit/hyperactivity disorder (ADHD) subjects and controls were compared in terms of information processing. Reaction time (RT), error-related negativity (ERN), P200, N200 and P300 were examined [112]. The subjects used a button-press to respond to rare (25% probability) Kanizsa squares (targets) among Kanizsa triangles (rare non-target distracters, 25% probability) and non-Kanizsa figures (standards, 50% probability). The results did not show differences in reaction time to target stimuli among groups. No differences in reaction time were seen, but both ASD and ADHD subjects committed more errors. In the context of neurophysiologic measures, the ASD group also demonstrated an attenuated error-related negativity (ERN) as compared to ADHD and control groups. The fronto-central P200, N200, and P300 were enhanced and less differentiated in response to target and non-target figures in the ASD group. The same ERP components were marked by more prolonged latencies in the ADHD group as compared to both ASD and typical controls. In autism, a model of local hyperconnectivity and long-range hypoconnectivity explains many of the behavioral and cognitive deficits present in the condition, while the inverse arrangement of local hypoconnectivity and long-range hyperconnectivity in ADHD explains some deficits typical for this disorder.

3.6.3. Ataxia: PPC and visual-to-motor transformation

In everyday life, we often interact with objects; for this to occur, humans need a high degree of accuracy to capture objects around [113]. This behavior typically occurs without considerable effort, though it requires a fast sensory processing of visual stimuli and proprioceptive information for continuous movement control [114]. Besides this, eye–hand coordination is essential to perform reaching movements, allowing interaction with the environment [115,116]. Failures in these mechanisms lead to optic ataxia (OA), i.e., the inability to precisely reach visual targets, which has been described extensively in the latest years [117,118].

The OA is a neurological disorder associated with damage of the visuomotor parietal cortex that occurs in the presence of visual or motor deficit [112,118–123]. The subject can identify the hand position, but cannot direct it towards an extrafoveal target [112]. Specifically, the patient demonstrates an inability to use sensory information (visual) for proper hand position [120] when the target is localized in the peripheral visual field [3,120,119]. Meanwhile, this problem is inexistent in central viewing conditions (foveal vision), where the subject can guide the eyes and head toward the object, [113,115,116,124,126].

The OA disorder provides an introduction to the way visual information is used by the perceptual motor system to control action. Patients who have the disorder fail to identify peripheral visual targets, but are able to reach targets through proprioceptive and auditory information [3]. This confirms that OA causes no damage to the motor system and does not impair spatial localization. Therefore, the observed visuomotor deficits have been related to failure in transforming the visual information to produce a coordinate action, and an impaired online visual control, i.e., the difficulty of updating the trajectory of motion [121].

The parietal cortex plays a major role in the visuomotor processing and transformation coordinates [107,115]. Lesion of the PPC, specifically of the dorsal stream, superior parietal lobule and parieto-occipital junction of the intra-parietal sulcus, are responsible for OA [113,115,120,123,125]. The involvement of these brain areas alters the representation of the visual space contralateral to the damaged hemisphere, and the movement of the contralesional hand becomes more impaired as the target becomes more eccentric [113,120]. The parieto-occipital junction is activated during the identification of targets in the peripheral visual field, and is responsible for updating online control along with the intra-parietal sulcus [3,125]. The superior parietal lobe controls visually guided reaching tasks and is responsible for tactile object recognition [111]. The patient with OA is able to describe the direction of an object, but cannot match the hand movement to reach the object, demonstrating that there is damage in the PPC dorsal stream, a crucial structure for the maintenance of visual awareness and for the identification of the object spatial properties [125]. Given the strategic location of the parietal cortex between the frontal and occipital lobes, OA was conceived as a disability emerging from a disconnection between the visual input and output of motor commands [122].

An impaired updating in OA has been associated to altered attention mechanisms, such as negligence; in a study using saccadic eye movement, the authors suggest that failures could be avoided if a temporal gap was introduced between the offset of the first target and the beginning of the second one [115]. In addition, a recent research found that OA patients start the eye movement later than healthy subjects [3].

3.6.4. Parkinson's disease: fronto-parietal net and spatial working memory

Parkinson's disease is a neurodegenerative disorder characterized by progressive functional and cognitive decline mainly due to dopamine depletion in subtantia nigra pars compacta, intra-neuronal Levy body inclusions and dopamine deficiency in basal ganglia and subthalamic nucleus [127]. The loss of nigral modulatory influence on the basal ganglia disrupts the physiologic function within cortico-basal ganglia–thalamic–cortical circuits [128,129]. It leads to several impairments in motor and non-motor neurological function, as damages in the visuospatial and executive system, memory, motor performance, beyond autonomic and psychiatric disturbances [130]. The motor complications include postural instability, resting tremor, muscular rigidity, akisesia, gait abnormalities, flexed posture and freezing [131,132]. The motor and non-motor impairments must be taken into account in therapeutic approaches; however, the present review is focused in non-motor aspects of Parkinson's disease. From this point of view, deficits in visuospatial and executive systems and specific aspects of memory have been mainly associated to cognitive impairments of Parkinson's disease [133,134]. The 3D mental rotation, linear orientation and memory tests for spatial localization have shown visuospatial deficiencies in patients with Parkinson's disease [135–138]. However, little is known about the brain mechanisms related to these visuospatial deficits [133].

In a study by Galtier et al. [134] visuospatial learning was assessed in 20 Parkinsonians without dementia. The authors associated this type of learning impairment with irregularities in the spatial working memory and visual spatial perception, and suggested that dysfunctions might be present in the cortico-striatal circuit, which includes the PPC. An earlier study conducted by Masure and Benton [139] reported that changes in spatial perception were the result of lesions in the PPC. On the other hand, deficits in spatial working memory are related to dysfunctions in the fronto-parietal network [137,140]. In addition, data obtained from functional neuroimaging showed a reduced metabolic rate in the parieto-occipital cortex, associated with the visuospatial performance of patients with idiopathic Parkinson's disease [141].

Pereira et al. [133] analyzed the correlation between gray matter density and visuospatial/perceptual performance in 36 non-demented parkinsonian patients. Patients performed less successfully than the control group in the Visual Form Discrimination Test, which consists of 16 items, each of them presenting a target set (model) and other stimuli that have four response options. Only one of these options is an exact copy of the model, while the other three contain errors such as distortion, displacement or rotation of the stimulus. The subject must decide which of the four options corresponds exactly to the target.

In brief, the results of different studies suggest a global impairment of visuospatial processes in Parkinson's disease, associated with dysfunction in different circuits, including the parietal lobes bilaterally, and the temporo-parietal, frontal–parietal and parietal–striatal networks [133,134].

3.7. Psychiatric aspects: schizophrenia, bipolar disorder and depression

Psychopathologic symptoms coming from parietal impairment may appear in many disorders. The IPL and temporal parietal junction regions in both hemispheres, and the left hemisphere language areas, present additional functional roles that may be related to symptoms such as: auditory and visual hallucinations; abnormalities in facial gesturing (unchanging expression, paucity, poor eye contact, lack of affective response and of vocal inflection, and inappropriate gestural responses); thought disorder and alogia; bizarre behavior; volition and attentional deficits; delusions of being controlled, of jealousy, of reference and persecutory; thought broadcasting, insertion and withdrawal; social withdrawal and asociality; flat affect and aggressiveness. These symptoms can be found in schizophrenic disorder and in other organic disorders with psychotic symptoms.

3.7.1. Schizophrenia: the inferior parietal lobule and the sense of self

Schizophrenia is a psychiatric disorder with the impairment of thought processes as a cardinal sign [4]. The disease also imposes an enormous turbulence in mood stability [142]. Common symptoms include auditory hallucinations, paranoid delusions, or disorganized speech and thinking, and it is followed by substantial social or occupational dysfunction [143]. Several experiments were conducted to examine the functional circuitry altered in schizophrenia which involves parietal regions associated with sense of self. For example, a network involving the inferior parietal lobule, superior parietal gyrus, precuneus, superior marginal and angular gyri was the most affected with different consequences related to the duration and severity of the illness (see Figs. 1 and 2). Smaller changes occurred in emotional memory and sensory and motor processing networks along with weakened interhemispheric connections. For instance, brain-wide functional connectivity changes in medicated schizophrenia patients, and functional connectivity changes were analyzed using resting-state fMRI data from 69 medicated schizophrenia patients and 62 healthy controls. Voxel-based morphometry was used to examine gray and white matter volume modifications. The functional connectivity changes with the strongest links to schizophrenia involved parietal instead of frontal regions [143].

3.7.2. Bipolar disorder: parietal region and misinterpretation of sensations

The bipolar disorder is associated with various neurobiological aspects with complex biochemical and molecular changes in brain circuits, related to neurotransmission and intracellular signal transduction [144]. Changes in neural function and glial cells have been associated with clinical depression and mania, the same way that brain homeostasis and metabolism dysfunctions have been associated with changes in the circadian rhythm, behavior and mood in bipolar disorder [145]. Furthermore, patients with bipolar disorder during episodes of mania (euphoria) show an extra vigilance accompanied by attention sub tenacity [146]. However, during the euphoria periods, the patients manifest superficial and dispersed attention, where they pause on environmental stimuli and have great difficulty to focus their attention on a specific object [147]. These comments were observed in a study, which also states that the parietal cortex is involved in manic and mixed episodes. Moreover, the deficits of the bipolar and unipolar depression were observed in the episodic memory [148]. Another study in post-mortem TB patients revealed a significant lower level of the 5-HIAA (hydroxyindoleacetic acid), which is the serotonin main metabolite in the frontal and parietal cortices. This fact provided evidence for the hypothesis that the central serotoninergic activity decreased in bipolar patients [145]. With the use of fMRI it has been observed that several cortical areas actively participate in various stages of the disorder, such as depression, hypomania and euthymia [149]. However, the area responsible for sensations and body orientation interpretation is found in the parietal cortex [150].

Using PET to analyze the depressive phase of individuals with bipolar disorder, the authors found a decreased activity in the prefrontal cortex and IPL (supra-marginal and angular gyri), and in corporal scheme, language, math operations and spatial localization areas [151]. The findings with photon emission tomography suggest, with some consistency, that a brain hypometabolism occurs during the depressive phase of bipolar disorder and, although with less consistence, that there is a tendency towards a hypermetabolism during the manic phase. These results involve different brain regions, yet abnormalities in the mesial temporal system occur only in depressive episodes. In the manic and mixed episodes there should be the involvement of the mesial temporal system, the fronto striatal and the PPC. In these studies, both in the unipolar and bipolar depression, the deficits were related to mnesic functions, specifically in episodic memory [152]. This fact was elucidated in a post-mortem study in the brains of bipolar patients, which provided evidence that there is a reduction in central serotonergic activity [145].

In another experiment using fMRI, depressed subjects showed reduced activation in the left IPL (supramarginal gyrus and angular gyrus) (see Fig. 1) with 50% of the patients showing a decreased neural response to fear [153]. This lack of activity in the left parietal cortex in response to fear may represent a reduced attention in depressed individuals [154]. Another interpretation could be based on the effect of antidepressant drugs, which reduce the identification of negative facial expressions of anger and fear [155]. Using cerebral blood flow in patients with bipolar disorder (mania) when compared to controls, it was observed that they significantly reduced the perfusion mainly in the left frontal area, in the left anterior cingulate and parietal cortex, while patients with bipolar depression reduced flow in the anterior temporal region bilaterally and in the left parietal region [156].

3.7.3. Major depression: PPC and allocation of conscious activities

In recent years, major depressive disorder has been pointed as being a mood disorder occurring with particular frequency. It is a serious disease that affects people of all ages, but lately, an increase of cases has been observed in young and elderly subjects [157]. This disorder is characterized by depressive mood, decreased energy and interest in performing certain activities, psychomotor retardation, appetite disorders, significant reduced self-esteem, guilt feelings and suicidal thoughts, affected memory and sustained attention deficits [158,159].

Recent studies have demonstrated that the nucleus accumbens (NAC), which is associated with pleasurable sensations and rewards, can play an important role in the etiology and pathophysiology of depression. A set of reactions involving several neurotransmitters culminate with the release of dopamine in the NAC, which receives the projections of dopaminergic cells located in the ventral tegmental area, a place of convergence for stimuli coming from the limbic system and part of the temporal lobe [160]. The NAC connections play a fundamental role in the regulation of motivation, emotion and cognition, motor reward and learning [161]. On the other hand, the parietal cortex has been suggested to be fundamental in the allocation of conscious activities for attention resources during episodic memory retrieval [8,162]. Attention is one of the cognitive functions traditionally associated with the PPC; however, its importance in the memory retrieval process has not been properly recognized. More recently, functional neuroimaging studies showed an active PPC during memory retrieval [8,163]. Therefore, the recovery of emotional memories seems not only to rely on the interaction between the medial prefrontal and temporal cortices, but also on the proper functioning of parietal areas [8,164].

4. Conclusion

In the present review we explored the participation of PC in different circumstances: sensory motor integration, hand movement control, saccadic eye movements, and neurological and psychiatric disorders. Thus, the main objective of this review was to extract relevant information supporting the idea that the parietal area is a key element to understand how the CNS is able to code different motor and sensory features in healthy and pathological instances. Supposedly, the parietal region has been associated with the sensory component in the integration process. In our discussion we emphasized this aspect, and we also observed that the parietal cortex has a key role in memory encoding and retrieving. Such aspect is fundamental when the CNS needs to translate sensory inputs into motor actions. We conclude that our review also showed that parietal cortex participates effectively in different neurologic disorders. PPC lesion, specifically of the dorsal stream, superior parietal lobule and parieto-occipital junction of the intra-parietal sulcus, is involved in different types of neurologic pathologies, such as: ataxia, stroke and Parkinson's disease. Our paper also pointed out that the parietal region is crucial in psychiatric pathologies. For example, the results showed that the mesial temporal system, the fronto-striatal and the posterior parietal cortex are key in manic and mixed episodes. Moreover, our research demonstrated that a decreased activation occurred within the posterior and inferior parietal regions involved in selective attention. Finally, the PPC involvement in many diseases needs the attention of neuroscientists because of its importance in affecting other areas and functions.

Conflict of interest

The authors have no conflict of interest to declare.

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