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How Humans Reach: Distinct Cortical Systems for Central and Peripheral Vision

SIMON CLAVAGNIER, JÉRÔME PRADO, HENRY KENNEDY, and MARIE-THÉRÈSE PERENIN

Lesions of the posterior parietal cortex in humans can produce a specific disruption of visually guided hand movements termed *optic ataxia*. The fact that the deficit mainly occurs in peripheral vision suggests that reaching in foveal and extrafoveal vision relies on two different anatomical substrates. Using fMRI in healthy subjects, the authors demonstrated the existence of two systems, differently modulated by the two reaching conditions. Reaching in central vision involves a restricted network, including the medial intraparietal sulcus (mIPS) and the caudal part of the dorsal premotor cortex (PMD). Reaching in peripheral vision engages a more extensive network, including the parieto-occipital junction (POJ). Interestingly, POJ corresponds to the site of the lesion overlap that the authors recently found to be responsible for optic ataxia. These two sets of results converge to show that there is not a unique cortical network for reaching control but instead two systems engaged in reaching to targets in the central and peripheral visual field. *NEUROSCIENTIST* 13(1):22–27, 2007. DOI: 10.1177/1073858406295688

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Reaching to touch and grasp an object in visual space is a routine and automatic action that nevertheless engages complex control systems in the posterior association cortex. The increased sophistication of the cerebral control system during evolution ensures an increase in accuracy and skill of the prehensile function, reaching its peak development in humans. However, this basic function belongs to an old repertoire of orientation behaviors involving not only the arm but also the eyes and head and, in infra-mammalian species, even whole-body movements for the purpose of prey catching. Although in lower species, such as the frog, this behavior is entirely controlled by subcortical structures such as the superior colliculus, in mammals and to an even greater extent in primates, there is a progressive increase in the role of the cortex (Ingle 1982; Milner and Goodale 1995).

Until recently, what we know about the neural substrate of reaching in humans was largely due to nature's own experiments—namely, from the disorders observed

following cortical lesions due to vascular injury, for example. Nearly a century ago, neurological observation pointed to the prominent role of the posterior parietal cortex. During the past 10 years, the development of functional imaging has provided an additional approach, making it possible to identify particular brain structures specifically activated when healthy subjects perform a given task. Due to the recent technical improvements in the spatial definition of both lesion and activation, a critical step has now been achieved. This allows neuropsychology to raise fundamental questions and use functional imaging to explain neurological disorders and suggest new experiments to be carried out in neurological patients.

When investigating the neural mechanisms underlying reaching movements, one has to take into account that humans do not have only one but two ways to reach and grasp objects: movements to be executed to targets in central and those to targets in the peripheral visual field. In fact, optimal accuracy is achieved when hand and eye movements are combined and subjects grasp an object following foveal capture. However, hand movements can also be made, albeit with less accuracy, without eye movements, such as when one reaches for a cup of coffee while continuing to read the newspaper. The decreased accuracy when reaching in the peripheral visual field could be due to the lower spatial resolution of peripheral vision. But this does not appear to be the sole difference between the two reaching conditions. In fact, as shown by psychophysical experiments, less accurate reaching is also observed when eye and hand are aimed conjointly at a visual target in the dark (Prablanc and others 1979; Vercher and others 1994).

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Fig. 1. Typical example of a patient with optic ataxia: (A) gross misreaching of the right hand for a target appearing in the right peripheral visual field and (B) spared reaching under foveal vision.

Optic Ataxia: When Neuropsychology Raises Fundamental Questions

Lesions of the posterior parietal cortex in humans can produce a specific disruption of visually guided hand movements, referred to as *optic ataxia* (Bálint 1909). Patients with optic ataxia exhibit large directional reaching errors accompanied by inappropriate hand shaping when grasping visual objects. Importantly, these reaching errors are found in the absence of any motor or pure sensory or visual deficit. A striking feature of optic ataxia is that patients fail in reaching and grasping at objects located in their peripheral visual field, but in most cases, they behave normally when allowed to orient their eyes and head toward the objects—that is, under conditions of central vision (Fig. 1) (Rondot and others 1977; Perenin and Vighetto 1988; Himmelbach and Karnath 2005; Jackson and others 2005; Karnath and Perenin 2005).

Based on early group studies, optic ataxia has been ascribed to lesions of the superior parietal lobule (SPL) and/or the intraparietal sulcus (IPS) (Ratcliff and Davies-Jones 1972; Jeannerod 1988; Perenin and Vighetto 1988; Milner and Goodale 1995). In a recent study, using new techniques of lesion analysis on larger groups of patients, including control patients without the target disorder (Rorden and Karnath 2004), it has been possible to define the core site of the lesions responsible for optic ataxia with much greater accuracy (Karnath and Perenin 2005). In this study, a group of 16 optic ataxia patients with unilateral lesions (10 with a left and 6 with a right hemisphere lesion) were compared to 36 stroke patients without that disorder. The latter control patients were either matched in associated neurological disorders (group A, $n = 16$) or selected for their lesion site, primarily including the parietal cortex (group B, $n = 20$). Superimposition and subtraction of lesions of optic ataxia and control groups revealed a center of overlap on the lateral convexity at the parieto-occipital junction (POJ) in both hemispheres—that is, the junction between the inferior parietal lobule (IPL), the SPL, and the superior

occipital cortex. In both hemispheres, the lesion overlap further extended via the underlying white matter toward the medial aspect of the hemisphere and included the precuneus close to the parieto-occipital sulcus (Fig. 2).

As all the 16 optic ataxia patients only misreached in peripheral vision, these results showed that POJ, together with the precuneus, corresponds to a region critically involved in this reaching condition and suggests that two different cerebral networks underlie reaching in central and peripheral vision.

The Functional Anatomy of Reaching: A Positive Image of Optic Ataxia

Previous functional imaging studies on reaching have led to somewhat conflicting results regarding the activated regions in the posterior parietal cortex. Earlier investigations, using PET, indicated specific activation in the intraparietal sulcus and the superior parietal lobule (Grafton and others 1996; Inoue and others 1998; Desmurget and others 2001). In contrast, more recent fMRI studies suggest, in addition to the foci obtained in the PET studies, an activity pattern in a more medial and posterior region of the parietal lobe (Simon and others 2002; Astafiev and others 2003; Connolly and others 2003).

Although all these studies have not addressed the issue of the cortical networks specifically involved in central and peripheral reaching, it is interesting to note that their apparent discrepancies may be due to the different conditions employed—namely, free-gaze reaching movements in the early PET studies and reaching to peripheral visual targets in the more recent fMRI experiments. Taken together, the results tend to support the hypothesis coming from optic ataxia literature that two distinct networks could be engaged during central and peripheral reaching.

To solve this question, we designed an event-related fMRI experiment in healthy subjects (Prado and others 2005). The participants were scanned while performing natural reaching movements (i.e., not just pointing in the

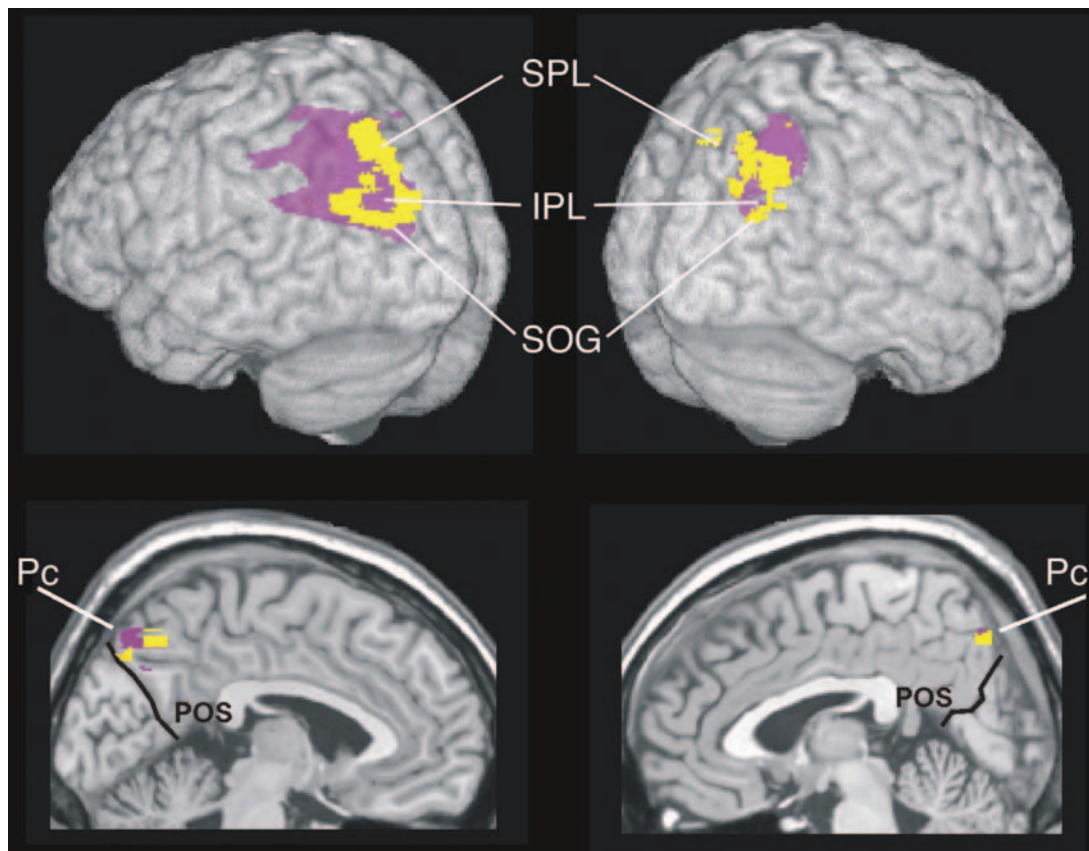


Fig. 2. Lateral and medial views of the center of lesion overlap in optic ataxia. Subtracted superimposed lesions of 10 left and 6 right optic ataxia patients minus 2 brain-damaged control groups, matched either for associated symptoms (pink area) or for lesion location, primarily involving the parietal lobe (yellow area). SPL, superior parietal lobule; IPL, inferior parietal lobule; SOG, superior occipital gyrus; Pc, precuneus. The parieto-occipital sulcus (POS) is shown in black on the medial views. Adapted from Karnath HO, Perenin MT. 2005. Cortical control of visually guided reaching: evidence from patients with optic ataxia. *Cereb Cortex* 15:1561–9. Reprinted with permission from Oxford University Press.

direction of the targets without touching them, as in most previous fMRI studies). In three experimental (e) conditions, they had to reach and touch a visual target appearing in their peripheral visual field, at 5 or 10 degrees, left or right from the midline. In two conditions, subjects were allowed to accompany their hand-reaching movement with an orientation saccade. In the first condition, the target remained visible throughout the whole trial and was thus captured by the fovea (visible target with saccade [VT/Se] condition). In a second condition, the target disappeared after 150 msec, thus prior to any foveal capture, and subjects had to touch the screen at the location where they had previously seen the target in their peripheral visual field (invisible target with saccade [IT/Se] condition). In a third condition, the target remained visible during the whole trial, but subjects were not allowed to make a saccade and instead had to maintain their eyes fixated on a central target (visible target with no saccade [VT/Nse] condition).

The rationale for having the hybrid IT/Se condition was to disentangle two potential confounding parameters of reaching performance: the presence or absence of eye movements and the peripheral versus central location of

the target. To know if there are differences in the cortical activation patterns in central and peripheral reaching, one also has to isolate the effects of the presence/absence of accompanying eye movements. Each of these three experimental reaching conditions was controlled (c) by conditions in which the visual stimulation was identical but participants were required to either orient their eyes toward the target (VT/Sc and IT/Sc) or to displace covert attention (VT/Nsc) without moving the arm.

It turns out that the determinant parameter concerning cortical activation is the retinal position, foveal versus extra-foveal, of the target and not the saccade per se. There were a number of common sites of activation in the left motor and somatosensory cortex and bilateral supplementary area (SMA), corresponding to the movement of the right hand found in the three experimental/control contrasts. The overall pattern of activation clearly shows that two different parieto-frontal systems are involved in reaching in the central and peripheral visual field. Reaching in the central vision task (VT/S) involves a rather restricted network, including the medial bank of the intraparietal sulcus (mIPS) bilaterally and the most caudal part of the dorsal premotor cortex

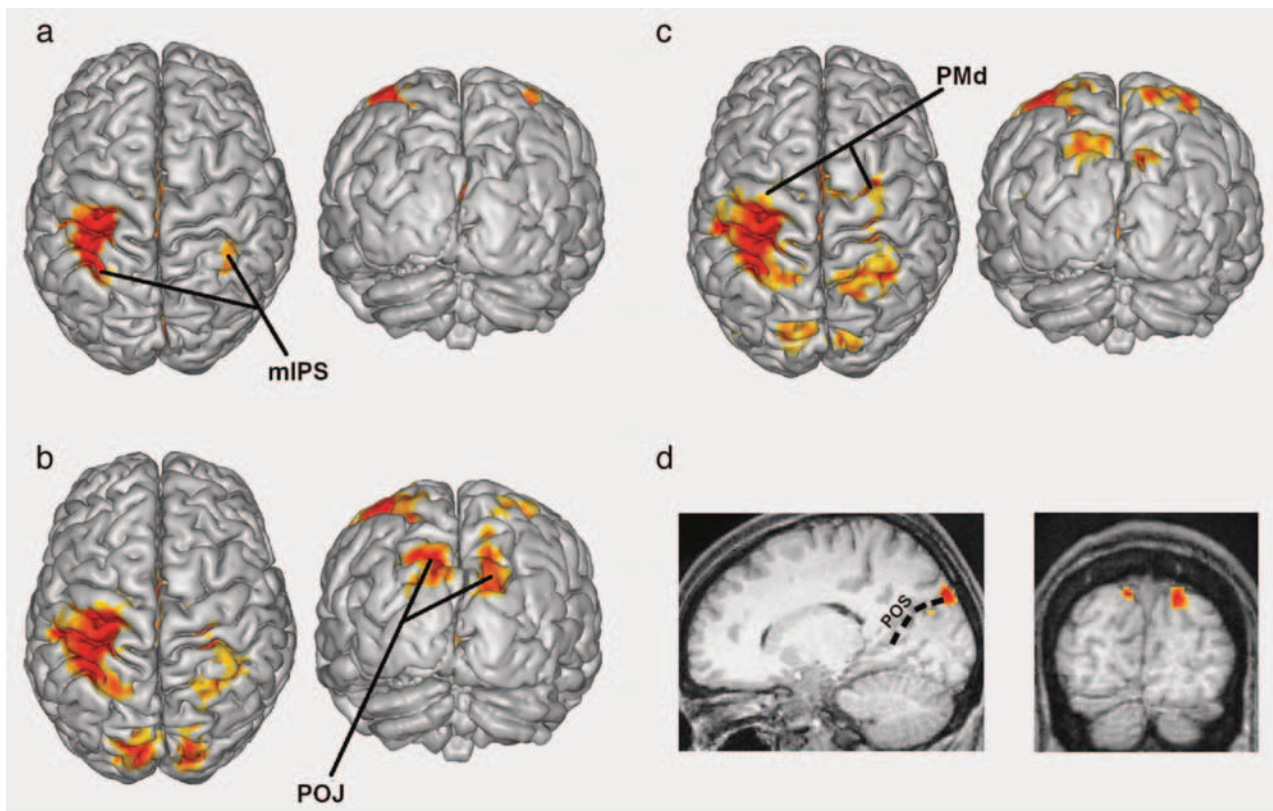


Fig. 3. Reaching in central or peripheral vision activates two different cortical networks, regardless of the presence or absence of eye movements. (a) Reaching in the visible target with saccade task (VT/S). (b) Reaching in the invisible target with saccade task (IT/S). (c) Reaching in the visible target with no saccade task (VT/NS). (d) Effect of the peripheral position of the target during reaching (direct comparison between IT/S and VT/S tasks). PMd, dorsal premotor area; mIPS, medial intraparietal sulcus; POJ, parieto-occipital junction; POS, parieto-occipital sulcus. Adapted from Prado J, Clavagnier S, Otzenberger H, Scheiber C, Kennedy H, Perenin MT. 2005. Two cortical systems for reaching in central and peripheral vision. *Neuron* 48:849–58. Reprinted with permission from Elsevier.

(PMd) on the left hemisphere (Fig. 3a). Reaching in peripheral vision (IT/S and VT/NS tasks) activates a more extensive cortical network, including the dorsal and medial parts of the POJ bilaterally and a more rostral part of the PMd in both hemispheres (Fig. 3b,c). Consistent with the above findings, direct comparison between IT/S and VT/S tasks confirmed that POJ and anterior PMd activations were specifically related to peripheral vision of the target during reaching (Fig. 3d).

Although direct comparison with monkey data is premature due to the lack of appropriate experiments, parieto-frontal circuits are engaged in reaching behavior in this species too. Among the different sites of activation that we have identified, the reaching-specific regions mIPS and POJ appear as likely homologs of the macaque medial intraparietal areas (Colby and Goldberg 1999; Galletti and others 1999). As area V6A preferentially projects to rostral PMd (Matelli and others 1998), this would fit with the increase of activity in both POJ and the rostral part of PMd during reaching movements to targets in the peripheral visual field.

Further Studies and Speculations on the Two Cortical Systems of Reaching

Both the fMRI and clinical studies provide converging evidence of two cortical control systems for reaching, with a parieto-occipital region specifically dedicated to reaching in the peripheral visual field. We have further evidence in favor of these conclusions from a lesion study of two patients with an extensive bilateral parieto-occipital injury resulting in a Bálint-Holmes syndrome, which rapidly gave way to a florid bilateral optic ataxia (Clavagnier and others, in preparation). Gross misreaching, predominating with the right hand, was observed in both cases but only for objects seen in peripheral vision. Although in the first patient (IG), optic ataxia has remained unchanged for several years, in the second patient (CF), the syndrome gradually improved after three months and eventually totally disappeared after five months. Interestingly, it was clear on high-resolution MRI scans that the lesions only partially overlapped (Fig. 4). On the convexity, the medial part of the IPS was

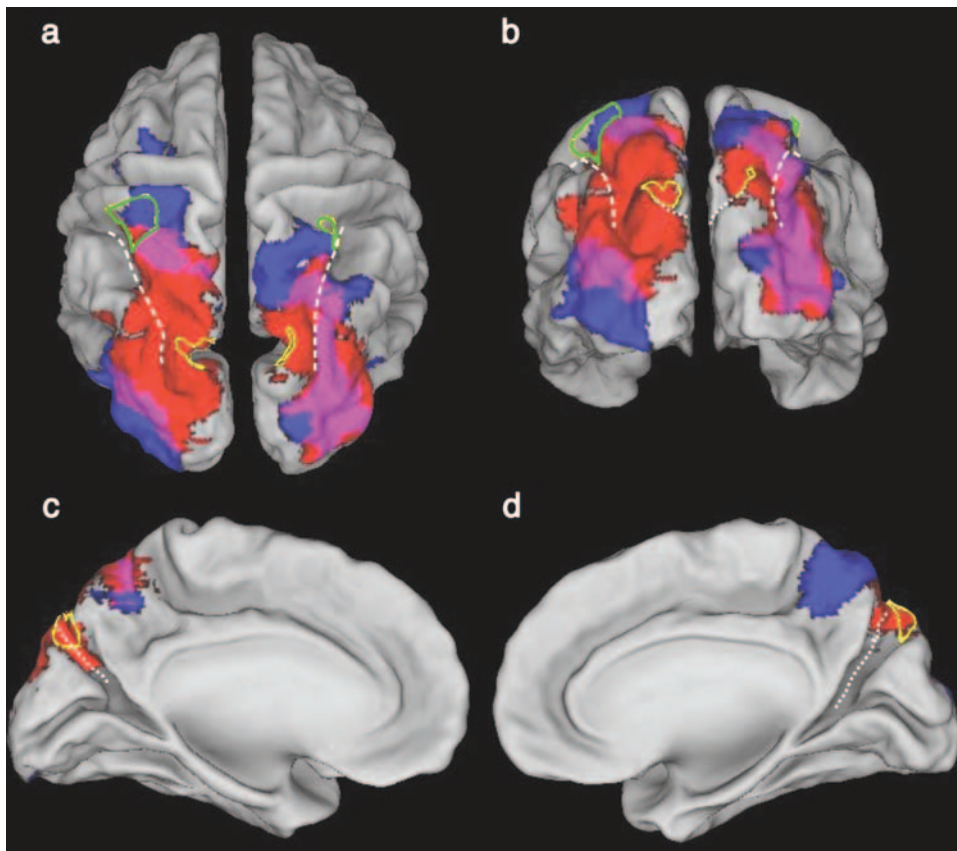


Fig. 4. Lesions of the optic ataxia patients IG (in red) and CF (in blue), superimposed on partially unfolded views of the two hemispheres, using Caret software (<http://brainmap.wustl.edu/caret>). (a) Dorsal view, (b) posterior view, and medial views of (c) the left and (d) the right hemispheres. The lesions of the two patients only partially overlap (pink region). The colored contours represent the two reach-related parietal areas found in Prado and others (2005): mIPS (green) and POJ (yellow). POJ, which is specifically activated by reaching in peripheral vision, has been damaged only in IG, who did not recover, in contrast to CF. Dashed line, intraparietal sulcus; dotted line, parieto-occipital sulcus. mIPS, medial intraparietal sulcus; POJ, parieto-occipital junction.

injured in both cases on the left hemisphere and in CF on the right. The major difference was observed in the parieto-occipital region. POJ was damaged only in IG, on both hemispheres, and more so on the left. On the medial side, the lesions of IG encroached on the upper part of the parieto-occipital sulcus. Thus, the region specifically activated by peripheral reaching in our fMRI study appeared entirely destroyed in the patient who failed to recover. This contrasted with CF, in whom only a more anterior part of the precuneus was damaged, which may explain why optic ataxia was only transient in this case.

Taken together, our findings support the existence of two cortical systems of reaching, respectively engaged in conditions of central and peripheral vision, which raises several important questions, the most important being why the brain is equipped with two separate reach-related regions—mIPS and POJ—in the parietal cortex.

In the two patients IG and CF, only impaired in peripheral vision, the lesion involved mIPS on one side. This could mean that mIPS does not fulfill a critical role in reaching to foveal targets in the way that POJ does for

peripheral targets. One possible function of mIPS could lie in the process of online automatic corrections, by which the ongoing motor command is modified during the reaching movement with respect to incoming changes from the sensory periphery. In fact, using these kinds of corrections—particularly when the target jumps at arm movement onset—is not possible in the patient IG (Pisella and others 2000) as well as in subjects with virtual lesions, using transcranial magnetic stimulation, centered on the IPS region (Desmurget and others 1999).

In a small minority of optic ataxia patients with large but still not well-defined lesions, misreaching is observed in not only peripheral but also central vision (Rondot and others 1977; Perenin and Vighetto 1988; Buxbaum and Coslett 1997). However, misreaching in uniquely central vision has never been reported. Hence, there is no evidence of a particular cortical region playing a critical role in the most natural reaching condition, when the target is captured in foveal vision.

It has been suggested that subcortical structures and the superior colliculus, in particular, could take part in the control of reaching in central vision (Milner and others

2003). These authors have argued that the medial bias of the directional errors (toward the fixation point), often observed in optic ataxia patients, would be reminiscent of the “magnetic misreaching” behavior that sometimes occurs after large cortical lesions (Carey and others 1997; Jackson and others 2005). In this extreme situation, patients are so severely impaired that they can no longer reach to a peripheral target, with their hand being systematically drawn to the fixated object. This could be regarded as a “primitive” form of reaching, possibly resulting from a lack of cortical inhibition of the superior colliculus. This cortical inhibition might be one of the major roles of POJ, which could be essential to decouple the spatial coordination between the eye and the hand during reaching. This type of process is not required when reaching is performed in central vision. On the contrary, the high accuracy and speed of movements performed in this condition appear to result from a tight coordination between eye and hand. In fact, a number of psychophysical experiments indicate that such an eye-hand coupling does exist (Fisk and Goodale 1985; Vercher and others 1994; van Donkelaar 1997; Sailer and others 2000). However, the neural mechanisms of eye-hand coordination are still poorly understood, and investigations in this field are just starting to open a new area of research.

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