CellPress
REVIEWS

Review

Comparing Parietal Quantity-Processing Mechanisms between Humans and Macaques

Ben M. Harvey,[1,2,*] Stefania Ferri,[3] and Guy A. Orban[3]

Quantity processing studies typically assume functional homology between regions within macaque and human intraparietal sulcus (IPS), where apparently similar locations respond to broadly similar tasks. However, macaque single cell neurophysiology is difficult to compare to human functional magnetic resonance imaging (fMRI); particularly in multivoxel pattern analysis and adaptation paradigms, or where different tasks are used. fMRI approaches incorporating neural tuning models allow closer comparison, revealing human numerosity-selective responses only outside the IPS. Extensive functional similarities support this novel homology of physical quantity processing. Human IPS instead houses a network responding to comparisons of physical quantities, symbolic numbers, and other stimulus features. This network likely reflects interactions between physical quantity processing, spatial processing, and (in humans) linguistic processing.

Two Quantity-Processing Networks in Human Parietal Cortex: a Proposal

Understanding numbers and quantities is vital to survival, facilitating foraging and hunting [1]. As such, numerical and quantitative cognition is common to many animals, being found from newborn chickens [2,3] and crows [4] to **macaques** (see Glossary) [5–8]. However, numerical and quantitative cognition is greatly expanded in humans, interacting with our unique linguistic and symbolic abilities to yield symbolic numerical and mathematical cognition [9].

Studies of quantity processing networks in humans and macaques identify an important role for the **intraparietal sulcus (IPS)** in both species [6,8,10–13], together with frontal areas. This has led to the suggestion that the IPS has similar functions in both species [12–14]. However, this is complicated by use of different stimuli, tasks, and experimental methods in these species; all of which affect the resulting responses. Studies of macaque quantity processing use single neuron spiking responses to **physical quantities** like **numerosity** (the number of visual objects in a display) in match-to-sample tasks. Human studies use **functional magnetic resonance imaging (fMRI)**; either physical quantities or **symbolic numbers**; and either passive viewing, comparison, or simple mathematical tasks. IPS locations of macaque physical quantity processing and some types of human quantity processing have demonstrated broadly similar areas responding to these broadly similar tasks, but this is insufficient to establish functional homology.

The different experimental techniques available to study neural responses and their cortical organization in humans and macaques complicate comparisons between species. Results

Trends

Human IPS was thought to have tuned responses to physical quantities like numerosity as macaque IPS contains such responses and human IPS is activated in some fMRI quantity processing paradigms.

Comparing human fMRI to macaque single neuron responses is difficult when using different tasks or fMRI paradigms without straightforward neural response interpretations.

fMRI paradigms incorporating explicit neural encoding models show physical quantity responses only outside human IPS.

Human IPS responds to comparisons of physical quantities, symbolic numbers, and nonquantitative features alike, forming a distinct network from selective responses to physical quantities.

This highlights the difficulty of comparing human and macaque neural responses to different tasks, measured with different methods. Macaque fMRI and encoding model analyses of human fMRI data help bridge this gap.

[1]Experimental Psychology, Helmholtz Institute, Utrecht University, Heidelberglaan 1, Utrecht, 3584 CS, The Netherlands
[2]Faculty of Psychology and Education Sciences, University of Coimbra, Rua do Colégio Novo, 3001-802, Coimbra, Portugal

from single cell recordings do not easily translate to fMRI, or vice versa. fMRI studies using repetition suppression (i.e., fMRI **adaptation**) and **multivoxel pattern analysis** (**MVPA**, i.e., decoding) are increasingly common, but their interpretation in terms of single neuron activity and its cortical organization is particularly difficult (Box 1). Other experimental paradigms that attempt to bridge this gap, either by incorporating encoding models of neural response into fMRI analysis [15–20] or measuring macaque neural responses with fMRI [21–23], are vital to allow comparisons between the two species.

Furthermore, the comparisons and mathematical tasks used in human studies appear to activate parietal areas, particularly the IPS's ventral bank (horizontal segment of the IPS, hIPS) [24], regardless of what is being compared. Conversely, macaque physical **quantity-selective responses** do not depend on the task performed [25].

Finally, relationships between locations in human and macaque brains are complex. Macaques have provided an excellent model of sensory systems; particularly vision. However, regions involved in more advanced cognitive functions become increasingly difficult to compare between humans and macaques. The human **parietal lobe** shows a tenfold expansion compared to that of macaques [26,27]; likely reflecting the evolution of language, advanced quantity processing, and advanced tool use networks in humans [9,28].

[3]Department of Medicine and Surgery, University of Parma, Via Volturno 39E, 43125, Parma, Italy

*Correspondence: b.m.harvey@uu.nl (B.M. Harvey).

Box 1. Inferring Neural Selectivity from fMRI

fMRI adaptation and particularly MVPA paradigms have become increasingly popular in recent years. However, both approaches are complex to interpret in terms of neural response selectivity and its cortical organization.

FMRI adaptation suppresses responses to adaptor stimulus states through repeated presentation. Changing stimulus state produces larger, less suppressed responses, with response recovery assumed to reflect the overlap of neural responses between adaptor and test stimulus states. This approach assumes that the stimulus selectivity of adaptation matches the stimulus selectivity of responses, but dissociations have been demonstrated [39]. Neural adaptation effects depend on several mechanisms, including sharpened tuning, response facilitation, response fatigue, and altered response dynamics [92,93]. Also, fMRI adaptation may reflect changes in neurovascular coupling rather than neural responsivity. Finally, fMRI adaptation in one area can reflect responses of its input pathways rather than responses of the activated area itself [39]. Here, if the hIPS has input pathways from areas with numerosity selective responses, this would predict hIPS activation even with no numerosity-selective populations here. Therefore, proper interpretation of fMRI adaptation would require comprehensive models of the neural populations involved, areas from which they receive inputs, various effects of adaptation on their activity, and their links to the vasculature [94].

MVPA is even harder to interpret. Here, any stimulus-linked change in fMRI response patterns allows decoding. Although initially assumed to reflect differential activation of fine-scale cortical structures with different response selectivities [95], subsequent investigations implicate larger structures [96–99] or even peculiarities of the stimulus setup with little relation to the property being studied [100,101]. Therefore, neural response selectivity may only be accessible to MVPA paradigms if mirrored by large-scale cortical organization [102]. Sources of MVPA decoding are still debated, but it remains impossible to confidently link MVPA decoding to neural response preferences.

Because of these difficulties of inferring neural responses selectivity with these approaches, we advocate two methods to reduce the gap between human and macaque studies. First is macaque fMRI with human fMRI paradigms, allowing direct comparison of similar responses in human and macaque brains. This also reveals the macroscopic and mesoscopic organization of macaque cortex, which is difficult and painstaking using single neuron recordings alone [19,86–88]. Second is human fMRI with neural encoding model paradigms, such as population receptive field modeling [103]. This specifically interprets fMRI responses in terms of underlying neural response selectivity.

Nevertheless, comparisons between fMRI and direct neurophysiological measurement are inherently limited as fMRI uses blood flow and oxygenation as proxies for electrical activity. The relationship between these is still not completely clear;, they are completely dissociated in some paradigms [104]; and fMRI primarily reflects local field potentials rather than spiking [105]. Finally, fMRI signals can reflect neural activity upstream along large draining veins, necessitating characterization of gross venous anatomy when assigning fMRI responses to neural activity at the same location [19,106].

Here, we compare quantity-processing networks in the parietal lobes of humans and macaques using a range of functional and structural criteria to evaluate homology. We propose that human quantity processing comprises two major parietal networks. The first is a physical quantity-processing network (sometimes called an analog magnitude system [29]) that is common to humans and nonhuman primates and interacts with a range of cognitive, perceptual, and motor networks. The second is a comparison processing network that has not been distinguished in macaques. This may have developed from interactions between the physical quantity-processing areas, spatial processing areas, and motor planning areas (in both species) and linguistic areas (in humans). In humans, these are complemented by a third mathematical cognition network involving linguistic processing areas inside and outside the human parietal lobe.

Neurophysiology of Macaque Parietal Numerosity Processing

The macaque parietal quantity-processing network is centered on the **fundus** of the IPS. Approximately 20% of neurons here respond selectively to the visual presentation of small numbers of objects, or numerosities [8]. These numerosity-selective neurons respond maximally when a specific number of objects is shown to the macaque, and response amplitudes decrease gradually with distance from this preferred numerosity. This tuning is similar for different stimulus configurations that keep lower order features such as display luminance or contrast constant. While delayed match-to-sample tasks are typically used in macaque studies, these selective responses do not rely on training, and the macaque does not need to perform a task using the presented numerosity [25].

Neuroimaging of Human Parietal Quantity Processing

Early **neuroimaging** of human parietal quantity processing investigated parietal activations during comparisons of numerosity or symbolic number, rather than responses to specific numerosities or numerals [30–35]. These studies consistently show human IPS activation during comparisons of both symbolic numbers [30–32] and various stimulus features, including numerosity [34,36], object size [35], duration [36], brightness [35], color [34], and differences in orientation [37]. These responses are not specific to physical quantity or symbolic number comparison [34] and are not found without comparison tasks [24]. Parts of this activated region may or may not be specific for number comparisons [32,34,35].

The discovery of numerosity-selective neurons in macaques led to the investigation of human parietal numerosity-selective responses using advanced fMRI methods. The earliest approach builds on the decrease in neural and fMRI responses with repeated stimulus presentation, known as fMRI adaptation or repetition suppression [38]. Because numerosity-selective neurons change their responses gradually with changing numerosity, responses will recover more after numerosity adaptation as the difference between the adapter and test numerosity increases. Using this approach, researchers were first able to indirectly measure numerosity-selective responses using fMRI [13]. The second approach, MVPA, was used to decode which numerosity was shown, using differences in spatial patterns of fMRI activation by different numerosities [12]. Again, activity patterns diverged with numerical distance.

These two approaches both suggest that single fMRI recording sites have numerosity-selective responses and/or that preferred numerosity changes across the cortical surface. However, the results of both approaches are difficult to interpret in terms of neural response selectivity and its cortical organization (Box 1). In particular, fMRI adaptation studies consistently show apparently numerosity-selective responses in the hIPS. However, fMRI adaptation paradigms show activation both in areas with selective neural responses and areas that receive input from responsive areas [39]. As the comparison network of the hIPS likely has inputs from areas with numerosity-selective responses, the activation of these areas alone should produce apparently

Glossary

Anterior intraparietal area (AIP): area at the anterior end of the macaque lateral IPS bank. Involved in sensorimotor transformations underlying the planning of manipulative actions. Separated here into a posterior, visually-responsive part (AIPv) and an anterior part that responds during motor actions (AIPm). AIPv is considered part of LIP in some studies.
Adaptation: decreased response to a stimulus after repeated presentation of an adaptor stimulus. fMRI adaptation (or repetition suppression) experiments use this specific decrease in neural activity to infer the response preferences of the brain.
Animal model: nonhuman animal used during research to investigate human physiology or pathology without the risk of harming humans.
Caudal intraparietal (CIP) area: area in the lateral bank of the posterior IPS of the macaque. Involved in the processing of 3D surfaces.
Dorsal intraparietal sulcus anterior (DIPSA): area of human anterior IPS responding to visual motion. Ventral DIPSA is a likely homolog of macaque posterior (visual) AIP. Dorsal DIPSA is a proposed homolog of anterior macaque VIP.
Dorsal intraparietal sulcus medial (DIPSM): area of human medial IPS responding to visual motion. Ventral DIPSM is the homolog of anterior macaque LIP.
Fundus: deepest part (bottom) of a brain sulcus.
Inferior parietal lobule (IPL): part of the human and macaque parietal lobe ventral to the IPS and posterior to the postcentral sulcus.
Intraparietal sulcus (IPS): major sulcus running approximately anterior to posterior through human or macaque lateral parietal lobe, segregating the superior from the inferior parietal lobule. The IPS contains many distinct brain areas in both species.
Homology/homologous/homolog: brain areas in different species that have evolved from the same area in a common evolutionary ancestor and perform similar functions. To assess homology consideration of many different species is desirable. In presence of only two species the

numerosity-selective responses in the hIPS. Furthermore, adaptation paradigms alternate periods of unchanging numerosity with periods where numerosity changes. These changes may implicitly cause individuals to make comparisons, activating hIPS.

Numerosity selectivity and its cortical organization have since been measured more directly using fMRI encoding model-based analyses that specifically incorporate models of neural numerosity selectivity to predict the responses of each individual recording site to the sequence of presented numerosities [19]. This revealed numerosity-selective responses in each recording site, and a gradual progression of preferred numerosity across the cortical surface, forming a finely organized **topographic map** of numerosity. This map sits in the **superior parietal lobule (SPL)**, dorsal to the IPS and posterior to the **postcentral sulcus**. Recent work [16] has demonstrated that this numerosity map is one of three topographic numerosity maps in the vicinity of the human postcentral sulcus (named NPC1–3), with another, smaller map (NPO) at the superior end of the **parieto-occipital sulcus** (Figures 1 and 2 A,B). These numerosity maps are all distinctly anterior and ventral to the IPS, in the postcentral sulcus and SPL. Figure 2C,D compares these locations to those identified by previous methods.

In summary, since the discovery of numerosity-selective neurons in macaques, increasingly advanced fMRI techniques have demonstrated numerosity-selective responses increasingly directly and revealed increasingly detailed pictures of their cortical organization. This has revealed numerosity-selective responses, organized into topographic numerosity maps, in and around the human postcentral sulcus (Figures 1 and 2), distinct from the comparison network of the hIPS.

Homology between Human and Macaque Quantity Processing

Macaques have provided an excellent **animal model** of the human brain; particularly in studying vision [40]. Like humans, macaques rely heavily on vision to guide behavior. Although the human cerebral cortex has roughly ten times the surface area of that of macaques [26,27,41], the human visual cortex is roughly five times larger than that of the macaque; a smaller expansion [23,41]. The human parietal cortex has expanded more, which has been attributed to the development of human linguistic, calculation, and tool use abilities [9,28] that are absent or limited in macaques. Indeed, the human **inferior parietal lobule (IPL)** has expanded more from macaques than the SPL has [42], systematically shifting macaque IPS areas to more dorsal sites in the human SPL [43,44].

Given this systematic shift and the elongation of the human IPS, what is the homology between macaque and human quantity-processing areas? Figures 1 A,B and 2 C,D show locations of **putative human anterior intraparietal (phAIP)**, **dorsal intraparietal sulcus anterior (DIPSA)**, **dorsal intraparietal sulcus medial (DIPSM)**, **ventral intraparietal sulcus (VIPS)** and **parieto-occipital intraparietal sulcus (POIPS)** confidence ellipses. These largely correspond to the lateral bank of the macaque IPS [44], shown in Figures 1 C,D and 2 E,F, but lie on the medial bank of the human IPS and in human SPL. Immediately anterior and medial to these ellipses, we find three human numerosity maps, NPC1–3 (Figures 1 A,B and 2 A–D). If these were similarly topologically positioned relative to the lateral bank of the macaque IPS, they should occupy the fundus of macaque IPS. Indeed, macaque **ventral intraparietal area (VIP)** is located in the fundus of the IPS [45] and this fundus also has a high density of numerosity-selective neurons (Figures 1 C,D and 2 E,F) [8]. Recent experiments specifically attribute numerosity-selective neurons specifically to parietal area VIP [46–48].

The human VIP homolog (the dorsal part of DIPSA [44,49]), like macaque VIP, is sensitive to optic flow, tactile stimulation, and intrusions into personal space [50–53], together with numerosity and object size tuning [18] (Table 1). This lies in the SPL, posterior to the posterior

homology is more difficult to establish and requires consideration of as many different functional and anatomical properties of the areas as possible.

Lateral intraparietal area (LIP): area of the lateral bank of macaque IPS involved in controlling eye movements and attention.

Macaque: rhesus macaque monkey (*Macaca mulatta*) is a common animal model of human brain function for medicine and neuroscience. Macaques are the closest evolutionary relative of humans commonly used in scientific experiments.

Multi-voxel pattern analysis (MVPA): common fMRI analysis method. MVPA uses changes in the pattern of activation within a brain area (rather than changes in the average activation of that brain area) to predict (classify) the stimulus or task presented to the subject.

Myelin: electrical insulating layer surrounding neuronal axons. The density of myelin changes between cortical regions.

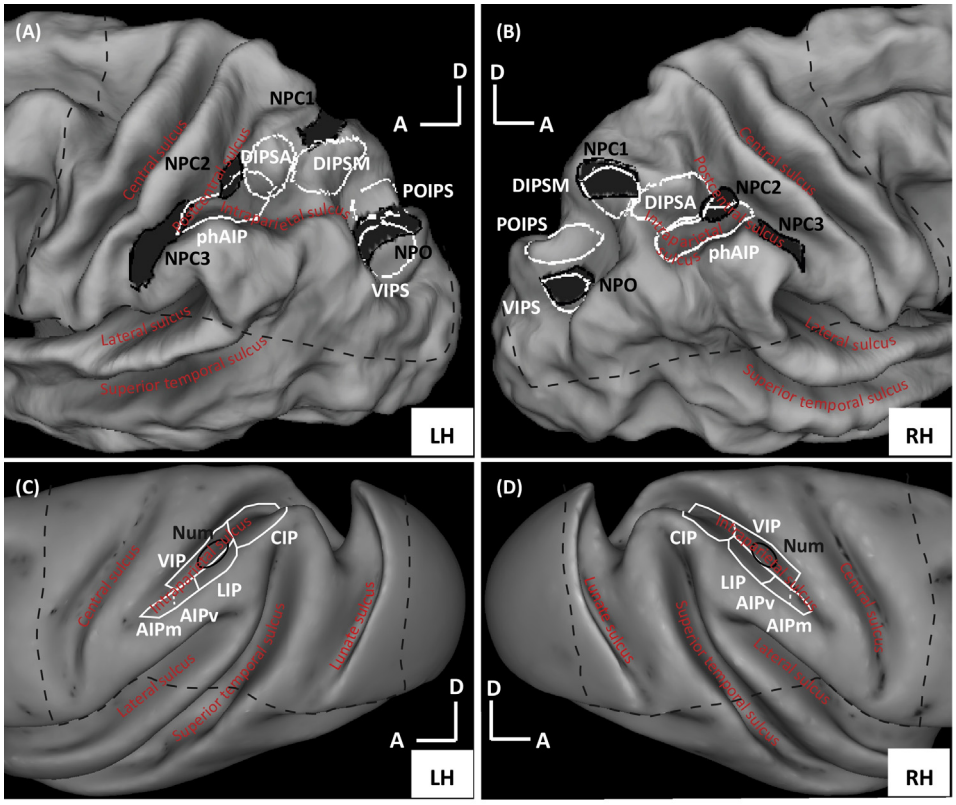
Numerosity: number of visual objects in an image.

Numerosity- or quantity-selective neuron or response: neuron or neuroimaging recording site that changes its response with changing numerosity or other quantity. The maximum response amplitude occurs at a specific preferred numerosity or quantity, with response amplitude decreasing with distance on both sides of this preferred numerosity of quantity.

NPC1, NPC2, NPC3, NPO: four recently discovered topographic maps of numerosity-selective neurons in the human parietal lobe. These are named by their anatomical locations: NPC1–3 are in and around the postcentral sulcus, while NPO is dorsal to the parieto-occipital sulcus.

Parieto-occipital intraparietal sulcus (POIPS): area of human posterior IPS responding to visual motion. Characterized by an emphasis on large eccentricities typical of the medial motion stream originating in V6.

Parieto-occipital sulcus: sulcus separating the parietal and occipital lobes of human and macaque brains. This runs ventral–dorsal, primarily up the medial surface of the brain and extends slightly onto the dorsal lateral surface.



Trends in Cognitive Sciences

Figure 1. Numerosity Maps in the Human and Macaque Parietal Cortex. Lateral views of posterior left (LH) and right (RH) hemispheres of human (A, B) and macaque (C, D) folded hemispheres. The four human parietal numerosity maps [16] are in black, with the parietal macaque area with the highest density of numerosity-selective neurons [8] shown as a black oval (Num). Confidence ellipses of human functional parietal areas responding to visual motion and activated by grasping [44] are shown in white, for comparison with subdivision of macaque intraparietal sulcus [55]. These are projected on the human PALS B12 [41] and macaque F99 [42] atlases using the Caret software package. Broken lines show approximate areas covered in the flattened representations in Figures 2 and 4. Abbreviations: AIP, anterior intraparietal area; AIPm, anterior motor part of AIP; AIPv, posterior visual part of AIP; CIP, caudal intraparietal area; DIPSA, dorsal intraparietal sulcus anterior; DIPSM, dorsal intraparietal sulcus medial; LIP, lateral intraparietal area; NPC, numerosity map in the vicinity of the human postcentral sulcus; NPO, numerosity map at the superior end of the parieto-occipital sulcus; phAIP, putative human AIP; POIPS, parieto-occipital intraparietal sulcus; VIP, ventral intraparietal area; VIPS, ventral intraparietal sulcus.

bank of the postcentral sulcus (Figure 3), immediately superior to the IPS [44,51,53], next to a peak in **myelin** density, which may be homologous to the ventral part of macaque **lateral intraparietal area (LIP)** [49]. This agrees well with the location of the human NPC1 numerosity map (Figures 1 and 2), and the functionally defined human VIP homolog allows highly accurate decoding of numerosity [51]. Therefore, it seems that both macaque VIP and its human homolog contain numerosity-selective neurons. Similarly, both macaque VIP [54] and a topographic map overlapping with NPC1 [18] exhibit object size-selective responses.

Further structural comparison could consider relationships between cytoarchitecture and connectivity. However, both properties can be characterized more precisely in macaques than humans. More accurate and detailed characterization of these properties in humans would be required to support comparisons to macaques.

Physical quantity: property of the world that can be measured, here by sensory systems. This includes (but is not limited to) numerosity, size, and event count.

Postcentral sulcus: major sulcus in the human anterior parietal lobe, located posterior to the central sulcus and meeting with the anterior part of IPS. The macaque postcentral sulcus is smaller and does not meet the IPS.

Putative human anterior intraparietal (phAIP): area responding to grasping execution, straddling both banks and fundus of the anterior human IPS. A likely homolog of macaque anterior (motor) AIP.

Resting state network: group of recording sites whose responses are correlated when subjects are not processing any stimulus or performing a specific task.

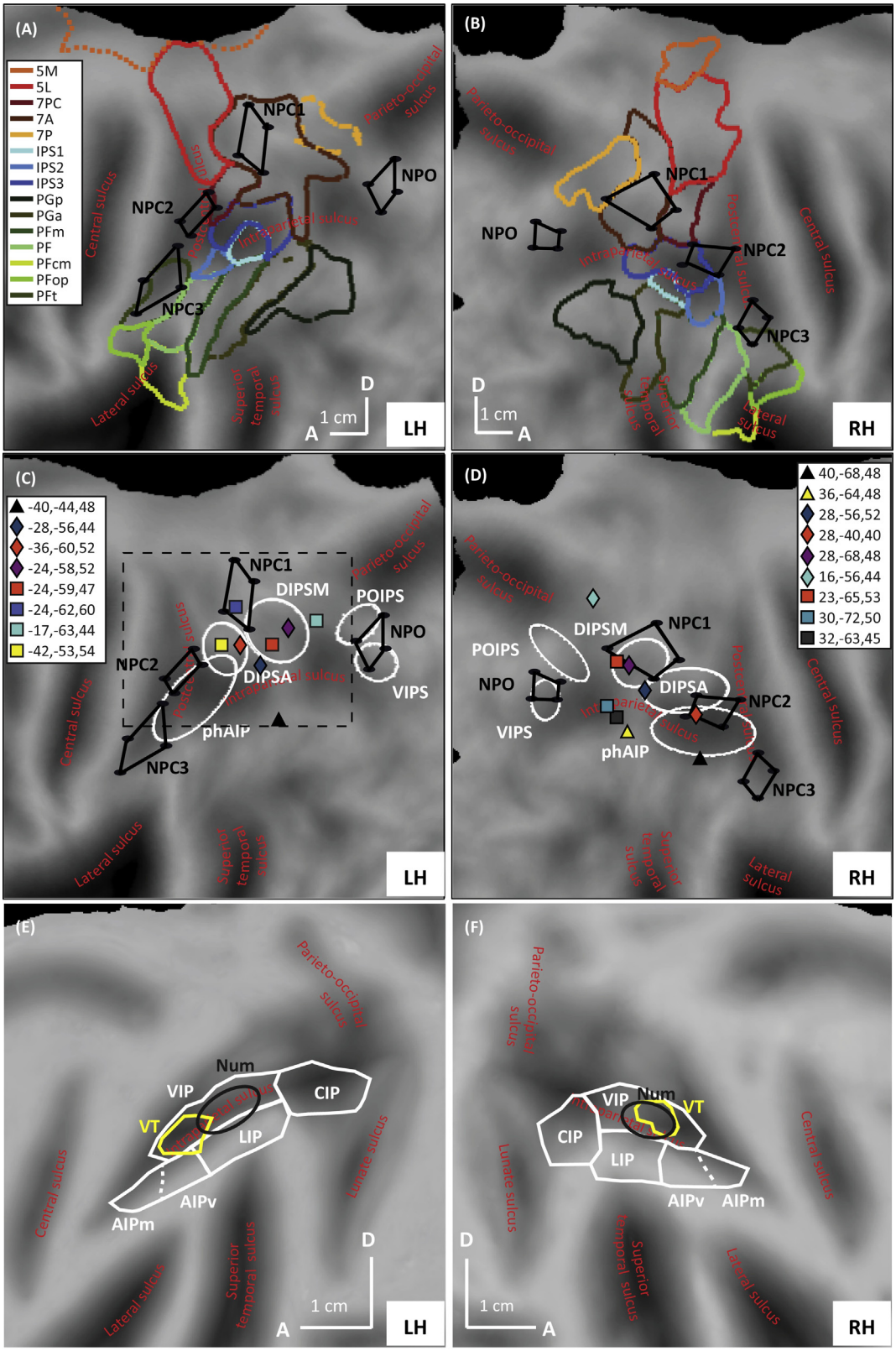
Superior parietal lobule (SPL): part of the human and macaque parietal lobe dorsal to the IPS and posterior to the postcentral sulcus.

Symbolic number/numeral: written Arabic numeral (e.g., 1, 2, 3, etc.). This is a symbol used to denote a magnitude of a particular physical quantities, rather than the physical quantity itself.

Topographic map: In neuroscience, a topographic map is a brain area in which response preferences gradually change across the cortical surface.

Ventral intraparietal area (VIP): area of the macaque IPS containing a large range of response preferences. Particularly important for multisensory integration, optic flow processing, and physical quantity processing.

Ventral intraparietal sulcus (VIPS): area of human ventral IPS responding to visual motion. A possible homolog of the macaque CIP. Approximately corresponds to human V7 and V7A or IPS0 and IPS1 visual field maps.



Trends in Cognitive Sciences

Figure 2. Architectonic and Functional Subdivisions of Flattened Parietal Cortex. Computationally flattened maps of left (A, C, E) and right (B, D, F) parietal lobes of human PALS B12 (A–D) and macaque F99 (E, F) brain atlases. Locations of human numerosity maps [16] and the parietal macaque area with the highest

(See figure legend on the bottom of the next page.)

In their definition of DIPSA as putative homolog of monkey VIP, Ferri and colleagues [49] followed the suggestion of Ben Hamed's group that VIP is functionally nonhomogeneous [55,56]. Optic flow selectivity, a hallmark of VIP [57] might be widespread in the whole VIP. By contrast, the region of visual tactile convergence and near space representation is located just anterior to the halfway point of VIP, abutting the regions where Nieder and Miller recorded numerosity selective neurons [8].

In both humans and macaques, physical quantity processing areas (NPC1 and the numerosity-selective neurons of VIP, respectively) are located immediately posterior to a region of visual tactile convergence (Figures 2 E,F and 3). Furthermore, visual optic flow stimuli activate a region centered close to and partially overlapping with NPC1 (Figure 3) [16,50], just as numerosity-selective neurons frequently exhibit optic flow responses [6,54].

Given the broad range of functional responses in macaque VIP, it may have expanded into several distinct areas spread across human parietal lobe. Hence, if NPC1 corresponds to this middle subpart of VIP, NPC2–3 may correspond to more anterior parts of VIP and NPO; possibly to its most posterior part. Alternatively, NPC2–3 and NPO may have no macaque homolog, or may correspond to uncharacterized macaque numerosity-processing areas.

Thus, recent fMRI studies have identified several numerosity maps in human SPL and postcentral sulcus. Extensive functional and structural similarities are required to confidently assign functional homology between brain areas in different species. Following such careful comparisons of their properties, NPC1 is the likely homolog of the middle subpart of macaque area VIP, where numerosity-selective neurons are reported (Figures 2 and 3). The other parietal numerosity maps may share a common evolutionary source with other parts of the VIP. We propose this ensemble of areas in both humans and macaques comprise a physical quantity-processing network representing the magnitude of sensory stimuli and small numbers of sensory- or motor-defined items in both species.

Generalization of Quantities in the Physical Quantity-Processing Network

One influential theory of quantity cognition proposes that physical quantities like numerosity and object size are processed together in a generalized magnitude network with space and time [58]. Several findings support the existence of such generalized quantity processing in both human and macaque parietal areas. In macaques, numerosity-selective neurons are found together with neurons selective for line length [54] and the number of events in a set [5,6]. In humans, recent work has demonstrated topographic maps of object size (Figure 3), partially overlapping with NPC1 and with correlated quantity preferences [18]. These results mirror behavioral interference between numerosity and object size perception [59,60]. It has been suggested that similar perception of different quantities reflect responses to a low-level stimulus feature that is common to several physical quantities [61,62], but recent behavioral studies provide evidence against this hypothesis [63]. Similarly, it has been suggested that neural responses to numerosity reflect a covarying low-level feature [62], but these responses follow numerosity closely regardless of its relationship to low-level features [17,19,64].

density of numerosity-selective neurons (Num) [8] are outlined in black. Their locations are shown relative to: (A, B) architectonic regions of IPL (green shades, see legend, [107]), IPS (blue shades, [108]) and SPL (red shades, [109]); (C, D) confidence ellipses (white) of human functional parietal areas responding to visual motion and activated by grasping [44], and local maxima of activations in other quantity processing studies (shapes), taken from [31] (triangles), [13] (diamonds) and [12] (squares); (E, F) subdivision of macaque intraparietal sulcus, and an area activated by visuotactile convergence (VT, yellow outline) [55]. Broken rectangle in (C) shows area covered in Figure 3. Abbreviations: AIP, anterior intraparietal area; AIPm, macaque AIP; AIPv, posterior visual part of AIP; CIP, caudal intraparietal area; DIPSA, dorsal intraparietal sulcus anterior; DIPSM, dorsal intraparietal sulcus medial; LIP, lateral intraparietal area; NPC, numerosity map in the vicinity of the human postcentral sulcus; NPO, numerosity map at the superior end of the parieto-occipital sulcus; phAIP, putative human AIP; POIPS, parieto-occipital intraparietal sulcus; VIP, ventral intraparietal area; VIPS, ventral intraparietal sulcus.

Table 1. Functional Response Shared by Macaque VIP and Its Human Homolog[a]

Feature	Monkey studies	No. of monkeys and type of recording	Human fMRI study	No. of subjects
Motion sensitivity	[57,112]	SC 2 monkeys fMRI 3 monkeys	[113]	13
Heading compatible optic flow	[114]	fMRI 3 monkeys	[50]	11
Intrusion moving objects	[115,116]	SC 3 monkeys SC 3 monkeys	[110]	8
Visuotactile convergence	[55,116,117]	SC 3 monkeys SC 2 monkeys fMRI 2 monkeys	[52]	24
Mirroring of intrusions	[118]	SC 3 monkeys	[49]	28
Numerosity selectivity	Nieder *et al.*[b] [119]	SC 11 monkeys SC 1 monkey	[16,19]	9
Object size selectivity	[54]	SC 2 monkeys	[18]	5
Topological position	[45]	Anatomy 10 monkeys	[49]	28

[a]SC, single cells.
[b]Several studies, total number from personal communication.

Whether this generalized magnitude network implies a common metric or arises from a common mechanism [65–68] has been heavily debated. Arguments in favor of this view include: (i) behavioral interference between different quantities and remarkably similar discriminability functions for different quantities [66]; (ii) similar cortical locations being activated by different quantities [65]; and (iii) generalized representation of physical number in some VIP neurons, with a population of long-latency VIP neurons responds similarly to both numerosity and visual event number [6], and some VIP neurons selective for auditory event number, some of which also respond to numerosity [5].

However, many other results support the opposite view. (i) The scaling between different quantities varies between trials in the same individual [69,70], suggesting behavioral mapping between quantities is flexible. (ii) Humans and macaques behaviorally distinguish changes in numerosity from changes in area, density, and size. Indeed, humans discriminate numerosity more sensitively than size or density [63,71], and these discriminations are affected remarkably little by other features [72]. (iii) Numerosity- and line length-selectivity are most frequently found in separate VIP cells [54]. Preferences for these two quantities are not correlated in the few cells that are selective for both. Similarly, numerosity- and object-size-selective neural populations form partially overlapping topographic maps [18]. However, these maps do not overlap fully, so some recording sites show one selectivity without the other. (iv) While population level numerosity and object size preferences are correlated, there is no consistent proportionality between these preferences, and the cortical progression of these two quantity preferences differs in direction [18]. (v) Cells responding to specific numbers of motor actions have been described in macaque SPL, but not in the IPS or area VIP [73], again suggesting nearby but distinct responses to different quantities within the parietal lobe.

Generalized magnitude processing also suggests links between representations of quantities and visual space [58,74]. Parietal numerosity- and object-size-selective neural populations lie at visually responsive sites with particular visuospatial receptive fields, and their topographic organization resembles topographic visual field maps [16,18,19]. However, there is no clear

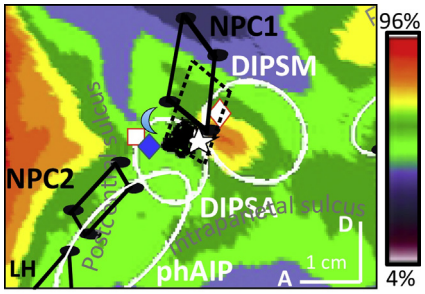


Figure 3. Dorsal DIPSA as Homolog of Monkey VIP. Numerosity maps (outlined in unbroken black) [16], the parietal object size map (outlined in broken black) [18] and confidence ellipses of functional parietal areas (white) [44] superimposed on computationally flattened maps of left parietal lobe showing myelin density (colors). Local maxima from various functional localizers of human VIP homolog are indicated by symbols. Moon: visuotactile integration [52]. Square: intrusion into peripersonal space [110]. Star: optic flow [50]. Silhouette: observation of interpersonal interactions [49]. Blue diamond: multisensory motion [51]. White diamond shows functional LIP localizer using saccades [51]. Dorsal DIPSA is the human functional homolog of the visuomotor part of VIP responsive to intrusion into peripersonal space. phAIP is the homolog of the anterior (motor) part of macaque anterior intraparietal area. Ventral DIPSA is the homolog of the posterior visual part of AIP. DIPSM is the homolog of the anterior part of LIP, and VIPS possibly of macaque caudal intraparietal area [44]. Modified from [49]. Abbreviations: AIP, anterior intraparietal area; DIPSA, dorsal intraparietal sulcus anterior; DIPSM, dorsal intraparietal sulcus medial; LIP, lateral intraparietal area; NPC, numerosity map in the vicinity of the human postcentral sulcus; phAIP, putative human AIP; VIP, ventral intraparietal area.

relationship between these representations: visual field position preferences are not correlated with quantity preferences; the borders of visual field maps and numerosity or object size maps do not coincide; and the relative positions of visual field maps and quantity maps differ between hemispheres and individuals.

In summary, recent results lead to a more nuanced view of generalized quantity processing in the physical quantity network, where neural populations selective for different quantities and visual space are located near each other. This may allow interactions between these populations, and may indeed underlie interference effects that prevent independent perception of different quantities. Similarities between quantity-processing networks may reflect shared computational constraints, working memory constraints, or decision processes for different quantities [68].

Symbolic Numerals and the Comparison Processing Parietal Network

Do symbolic numerals produce responses in physical quantity-selective neurons or activation sites? fMRI recording sites in NPC1 are selective for particular numerosities but not for particular symbolic numerals [19]. In macaques, extensive training to associate symbols with particular numerosities produces symbol-selective responses in only 2% parietal numerosity-selective neurons, compared to 23% of prefrontal numerosity-selective neurons, suggesting links between specific numerosities and symbols may rely far more on frontal than parietal areas [75].

The neuroimaging results suggesting shared parietal responses to physical quantities (primarily numerosity) and symbolic numerals representing the same number are inconclusive. Some lack spatial resolution [76]. fMRI adaptation experiments suggest such a shared representation in the hIPS [77]. Yet this area (Figures 2 C,D and 4) does not show numerosity-specific responses in other fMRI paradigms and changing from numerals to dot patterns causes a large recovery from adaptation, suggesting the resulting responses rely on different neural populations. Again, this may reflect implicit comparisons elicited by stimulus changes.

Key Figure

Three Quantity-Processing Networks in Parietal Cortex

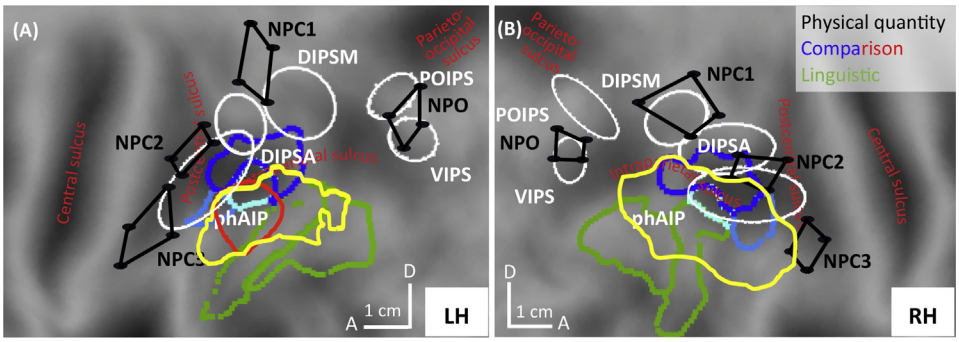


Figure 4. Computationally flattened maps of human left (A) and right (B) parietal lobe showing physical quantity (black), comparison (red/blue) and linguistic mathematical (green) processing networks. Numerosity maps (black outlines), confidence ellipses (white). HIPS (red) [11] and IPS areas [108] activated by strings of addition and subtraction [111] (blue) are distinct from IPL angular gyrus areas deactivated by strings of addition and subtraction [111] (green). A region of cortical expansion in humans, with no corresponding resting state network in macaques [82], (yellow) overlaps considerably with comparison and linguistic mathematical networks. Abbreviations: CIP, caudal intraparietal area; DIPSA, dorsal intraparietal sulcus anterior; DIPSM, dorsal intraparietal sulcus medial; NPC, numerosity map in the vicinity of the human postcentral sulcus; NPO, numerosity map at the superior end of the parieto-occipital sulcus; phAIP, putative human anterior intraparietal area; POIPS, parieto-occipital intraparietal sulcus; VIPS, ventral intraparietal sulcus.

MVPA of IPS and postcentral sulcus activity has been used to determine which numerosity was presented [12]. This method could also determine, less accurately, which symbolic numeral was presented. A distance effect was found for numerosity but not numerals, suggesting that responses to numerals are not represented in a continuous neural space, as physical quantities are. Subsequent work has suggested that entirely different regions support decoding of numerals and numerosity [78]. Furthermore, the response elicited by any symbolic numeral is always closest to that elicited by a numerosity of one [12,79], suggesting the physical quantity network primarily responds to the number of digits the symbolic numeral contains. MVPA classifiers trained on symbolic numerals fail to reproducibly distinguish numerosity [78–80], and vice versa [12]. Finally, individuals here performed comparison tasks for both numerosity and symbolic number, so similar responses may arise from similar tasks being performed rather than similar stimulus representations [35].

Several studies show activation of human IPS during both symbolic number and numerosity comparisons [30–35], but these areas are similarly activated comparisons of color, brightness and differences in orientation [34,35,37], so its responses do not appear to be specific to quantities.

Although macaques can perform comparison tasks, no homolog of the comparison processing network of the hIPS has yet been described in macaques. Macaque studies have not distinguished responses to the comparisons that the animals typically make from responses to the compared physical quantities. However, the responses described seem to follow the physical quantities as they do not require comparison tasks [25]. A small proportion of macaque VIP

cells (<10%, compared to 20% in prefrontal and premotor cortices) respond during numerosity comparisons [47], so macaque VIP may also have given rise to the human comparison processing network. Alternatively, macaques may use uncharacterized comparison areas outside VIP. Similar topological positioning relative to macaque VIP and its human homolog would predict comparison responses in macaque IPL or lateral IPS.

Comparisons and simple calculations with symbolic numerals activate the hIPS [9,11]. While macaques can compare and add nonsymbolic numbers [81], they lack our symbolic and linguistic skills. Therefore, the human comparison network may be more complex than in macaques. The hIPS lies in a region strongly expanding in humans compared to macaques [42,44], and in a **resting state network** with no macaque counterpart [82]. This network appears to build on the physical quantity-processing network present in macaques, perhaps through interactions with spatial processing and motor planning networks and, in humans, parietal linguistic areas.

In summary, comparisons activate parietal sites distinct from the physical quantity network in humans (Figure 4, Key Figure). It remains unclear which macaque brain areas respond to comparisons (see Outstanding Questions). While comparisons of physical quantities, symbolic numbers, and other visual features all activate this human comparison network, it remains unclear whether these each engage distinct neural populations.

Mathematics and Calculation: a Third Parietal Network

Human fMRI studies describe two numerical cognition networks involved in mathematical tasks. These were initially distinguished by exact and approximate mathematical tasks [83]. In an exact calculation task '4 + 5 =' might be followed by '9 or 7', that is, a correct answer and a close but incorrect answer. In an approximate task possible responses might be '8 or 3', that is, a close and a far incorrect answer. Approximate calculation activates the IPS and middle frontal gyrus, while exact calculation activates the left inferior frontal lobe.

Subsequent work (reviewed in [11]) showed IPS activation by subtraction and addition, with activation of the left angular gyrus, IPL, and inferior temporal gyrus [84,85] during multiplication and division based on rote learning (Figure 4). This suggests that simpler mathematical tasks may rely on the comparison network of the hIPS, so this may have a broader role in processing quantitative relationships. Again, it is unclear whether addition, subtraction, and comparisons engage distinct neural populations. More complex mathematics activate angular gyrus and a widespread linguistic processing network beyond the hIPS comparison network and the physical quantity network of the SPL and postcentral sulcus.

Concluding Remarks

The macaque IPS, particularly VIP, contains a high density of neurons with tuned responses to physical quantities like numerosity [8]. fMRI results implicate the human parietal lobe in representation and processing of various quantities and tasks: representing physical quantities (dorsal DIPSA and postcentral sulcus); comparing physical quantities, symbolic numbers, and stimulus features (hIPS); and simple mathematics (hIPS and left angular gyrus). The contribution of linguistic regions to complex mathematical tasks has clearly been distinguished. However, the remaining numerical cognition processes have been integrated into a single core semantic quantity area in the IPS [11,12,77] assumed to correspond to macaque parietal sites with physical quantity-tuned responses [14].

However, it is difficult to compare results from human fMRI studies and macaque single neuron recordings. The use of comparison tasks, and fMRI adaptation in human studies makes this

Outstanding Questions

How do the functional roles of the different numerosity maps differ? These respond to numerosity very similarly, but interactions with nearby areas may differ. NPC1 appears to correspond to VIP, so may be involved in multisensory integration of physical quantities. NPC2 and NPC3 lie near phAIP, so may be involved in manipulation. NPO lies near areas parsing 3D surfaces, so may allow scene element individuation.

Are there macaque functional homologs of numerosity maps besides NPC1? Macaque fMRI is a powerful tool to examine functional organization (as in the face patch network) and functional homology between human and macaque areas (as in comparative visual field mapping).

Are numerosity-selective responses also topographically organized in macaque? Macaque fMRI is better suited to demonstrate topographic organization than single neuron recordings are.

Does the physical quantity network show numerosity preferences above the subitizing range?

Are there human parietal areas with selective responses for other physical quantities like event numbers or timing?

The parietal areas in the physical quantity network are often implicated in multisensory processing. Are responses to physical quantities from sensory modalities other than vision present in human parietal cortex? Are responses to quantities of motor actions? Do these responses differ between senses?

How are physical quantity-specific responses computed from sensory inputs?

Do comparisons of different stimulus types engage distinct neural populations in the comparison network? Do comparisons, additions and subtractions engage distinct neural populations?

Does the macaque brain have a comparison network beyond VIP?

particularly problematic. This highlights a need for fMRI analyses based on neural encoding models, which explicitly interpret fMRI responses in terms of the underlying neural response selectivity. Performing fMRI experiments in macaques can also bridge the gap between human and macaque studies. Determining properties of cortical organization with single neuron recordings alone is a painstaking process, while fMRI recordings make the macroscopic and mesoscopic spatial organization of responses clear [19,86–88].

fMRI paradigms based on encoding models have recently revealed a more complex picture of human parietal quantity processing [16–19]. Several topographic maps in the SPL and postcentral sulcus represent physical quantities such as numerosity (Figures 1–4) and are close functional homologs of macaque VIP. These are distinct from human hIPS (red in Figure 4), which is involved in comparison tasks and simple mathematical operations. A third widespread linguistic network, with a parietal node in the angular gyrus, responds to multiplication, division, and complex mathematical tasks (green in Figure 4). This distinction will allow future research to investigate important outstanding questions about these three networks.

The lack of distinction between physical quantity processing and comparison networks highlights the difficulty in comparing human and animal brain responses using both different recording methods and different tasks. fMRI paradigms based on encoding models (whose design is inspired by animal neurophysiological studies) allow a more computational understanding of higher cognitive areas, moving beyond localization of these areas alone and allowing comparison to known response neural properties of animal models.

Ultra-high-field fMRI is becoming a valuable tool to distinguish specific responses within areas that have previously been assumed to respond homogeneously, thereby revealing mesoscopic organization in the human brain [89,90]. Topographic map organization, a mesoscopic cortical organization principle common across sensory systems, has thus been shown in physical quantity processing [16,18,19], demonstrating that mesoscopic organization extends to cognitive processing areas. Combined study of neural response selectivity and mesoscopic organization using ultra-high-field fMRI and encoding models may contribute a computational understanding of higher cognitive networks in humans and comparison to simpler animal networks. Similar encoding model-based analyses have also recently revealed the representation of linguistic semantic information, apparently completely lacking in animal models, directly in the human brain [91]. So, even where nothing is known from animal models about a specific system, general principles of neural encoding can still inspire fMRI paradigms. However, even highly sophisticated fMRI techniques are still limited by reliance of fMRI on hemodynamic responses, so direct invasive electrical recordings from the human brain provide a further important tool for comparison to macaque recordings.

What are the links/interactions between the three parietal quantity networks?

Does the human brain contain selective responses to specific symbolic numbers?

How are responses of the human physical quantity and comparison networks affected in developmental dyscalculia and acquired acalculia?

Acknowledgments

This work was supported by ERC grant 323606 Parietalaction, by Portuguese Foundation for Science and Technology grant IF/01405/2014 and by The Netherlands Organization for Scientific Research grant 016.175.414.

References

1. Vallentin, D. and Nieder, A. (2008) Behavioral and prefrontal representation of spatial proportions in the monkey. *Curr. Biol.* 18, 1420–1425
2. Rugani, R. *et al.* (2015) Animal cognition. Number-space mapping in the newborn chick resembles humans' mental number line. *Science* 347, 534–536
3. Rugani, R. *et al.* (2009) Arithmetic in newborn chicks. *Proc. Biol. Sci.* 276, 2451–2460
4. Ditz, H.M. and Nieder, A. (2015) Neurons selective to the number of visual items in the corvid songbird endbrain. *Proc. Natl. Acad. Sci. U. S. A.* 112, 7827–7832
5. Nieder, A. (2012) Supramodal numerosity selectivity of neurons in primate prefrontal and posterior parietal cortices. *Proc. Natl. Acad. Sci. U. S. A.* 109, 11860–11865
6. Nieder, A. *et al.* (2006) Temporal and spatial enumeration processes in the primate parietal cortex. *Science* 313, 1431–1435
7. Nieder, A. *et al.* (2002) Representation of the quantity of visual items in the primate prefrontal cortex. *Science* 297, 1708–1711
8. Nieder, A. and Miller, E.K. (2004) A parieto-frontal network for visual numerical information in the monkey. *Proc. Natl. Acad. Sci. U. S. A.* 101, 7457–7462

9. Simon, O. *et al.* (2002) Topographical layout of hand, eye, calculation, and language-related areas in the human parietal lobe. *Neuron* 33, 475–487
10. Cappelletti, M. *et al.* (2007) rTMS over the intraparietal sulcus disrupts numerosity processing. *Exp. Brain Res.* 179, 631–642
11. Dehaene, S. *et al.* (2003) Three parietal circuits for number processing. *Cogn. Neuropsychol.* 20, 487–506
12. Eger, E. *et al.* (2009) Deciphering cortical number coding from human brain activity patterns. *Curr. Biol.* 19, 1608–1615
13. Piazza, M. *et al.* (2004) Tuning curves for approximate numerosity in the human intraparietal sulcus. *Neuron* 44, 547–555
14. Nieder, A. and Dehaene, S. (2009) Representation of number in the brain. *Annu. Rev. Neurosci.* 32, 185–208
15. Dumoulin, S.O. and Wandell, B.A. (2008) Population receptive field estimates in human visual cortex. *Neuroimage* 39, 647–660
16. Harvey, B.M. and Dumoulin, S.O. (2017) A network of topographic numerosity maps in human association cortex. *Nat. Hum. Behav.* 1, 36
17. Harvey, B.M. and Dumoulin, S.O. (2017) Can responses to basic non-numerical visual features explain neural numerosity responses? *Neuroimage* 149, 200–209
18. Harvey, B.M. *et al.* (2015) Topographic representations of object size and relationships with numerosity reveal generalized quantity processing in human parietal cortex. *Proc. Natl. Acad. Sci. U. S. A.* 112, 13525–13530
19. Harvey, B.M. *et al.* (2013) Topographic representation of numerosity in the human parietal cortex. *Science* 341, 1123–1126
20. Kay, K.N. *et al.* (2008) Identifying natural images from human brain activity. *Nature* 452, 352–355
21. Arcaro, M.J. *et al.* (2011) Visuotopic organization of macaque posterior parietal cortex: a functional magnetic resonance imaging study. *J. Neurosci.* 31, 2064–2078
22. Kolster, H. *et al.* (2009) Visual field map clusters in macaque extrastriate visual cortex. *J. Neurosci.* 29, 7031–7039
23. Orban, G.A. *et al.* (2004) Comparative mapping of higher visual areas in monkeys and humans. *Trends Cogn. Sci.* 8, 315–324
24. Cavdaroglu, S. *et al.* (2015) Dissociating estimation from comparison and response eliminates parietal involvement in sequential numerosity perception. *Neuroimage* 116, 135–148
25. Viswanathan, P. and Nieder, A. (2013) Neuronal correlates of a visual "sense of number" in primate parietal and prefrontal cortices. *Proc. Natl. Acad. Sci. U. S. A.* 110, 11187–11192
26. Van Essen, D.C. *et al.* (2012) Cortical parcellations of the macaque monkey analyzed on surface-based atlases. *Cereb. Cortex* 22, 2227–2240
27. Van Essen, D.C. *et al.* (2012) Parcellations and hemispheric asymmetries of human cerebral cortex analyzed on surface-based atlases. *Cereb. Cortex* 22, 2241–2262
28. Peeters, R. *et al.* (2009) The representation of tool use in humans and monkeys: common and uniquely human features. *J. Neurosci.* 29, 11523–11539
29. Brannon, E.M. (2006) The representation of numerical magnitude. *Curr. Opin. Neurobiol.* 16, 222–229
30. Pinel, P. *et al.* (1999) Event-related fMRI analysis of the cerebral circuit for number comparison. *Neuroreport* 10, 1473–1479
31. Pinel, P. *et al.* (2001) Modulation of parietal activation by semantic distance in a number comparison task. *Neuroimage* 14, 1013–1026
32. Gobel, S.M. *et al.* (2004) Response-selection-related parietal activation during number comparison. *J. Cogn. Neurosci.* 16, 1536–1551
33. Pinel, P. *et al.* (2004) Distributed and overlapping cerebral representations of number, size, and luminance during comparative judgments. *Neuron* 41, 983–993
34. Shuman, M. and Kanwisher, N. (2004) Numerical magnitude in the human parietal lobe; tests of representational generality and domain specificity. *Neuron* 44, 557–569
35. Cohen Kadosh, R. *et al.* (2005) Are numbers special? The comparison systems of the human brain investigated by fMRI. *Neuropsychologia* 43, 1238–1248
36. Dormal, V. *et al.* (2012) A common right fronto-parietal network for numerosity and duration processing: an fMRI study. *Hum. Brain Mapp.* 33, 1490–1501
37. Fias, W. *et al.* (2002) The quantitative nature of a visual task differentiates between ventral and dorsal stream. *J. Cogn. Neurosci.* 14, 646–658
38. Grill-Spector, K. and Malach, R. (2001) fMR-adaptation: a tool for studying the functional properties of human cortical neurons. *Acta Psychol. (Amst.)* 107, 293–321
39. Sawamura, H. *et al.* (2006) Selectivity of neuronal adaptation does not match response selectivity: a single-cell study of the FMRI adaptation paradigm. *Neuron* 49, 307–318
40. Orban, G.A. (2017) Evolution of human visual system specializations. In *Evolution of Nervous Systems* (Kaas, J.H., ed.), pp. 227–247, Academic Press
41. Van Essen, D.C. (2005) Surface-based comparisons of macaque and human cortical organization. In *From Monkey Brain to Human Brain* (Dehaene, S. *et al.*, eds), pp. 3–19, MIT Press
42. Van Essen, D.C. and Dierker, D.L. (2007) Surface-based and probabilistic atlases of primate cerebral cortex. *Neuron* 56, 209–225
43. Grefkes, C. and Fink, G.R. (2005) The functional organization of the intraparietal sulcus in humans and monkeys. *J. Anat.* 207, 3–17
44. Orban, G.A. (2016) Functional definitions of parietal areas in human and non-human primates. *Proc. Biol. Sci.* 283
45. Lewis, J.W. and Van Essen, D.C. (2000) Corticocortical connections of visual, sensorimotor, and multimodal processing areas in the parietal lobe of the macaque monkey. *J. Comp. Neurol.* 428, 112–137
46. Ramirez-Cardenas, A. *et al.* (2016) Neuronal representation of numerosity zero in the primate parieto-frontal number network. *Curr. Biol.* 26, 1285–1294
47. Vallentin, D. *et al.* (2012) Numerical rule coding in the prefrontal, premotor, and posterior parietal cortices of macaques. *J. Neurosci.* 32, 6621–6630
48. Viswanathan, P. and Nieder, A. (2015) Differential impact of behavioral relevance on quantity coding in primate frontal and parietal neurons. *Curr. Biol.* 25, 1259–1269
49. Ferri, S. *et al.* (2015) The organization of the posterior parietal cortex devoted to upper limb actions: an fMRI study. *Hum. Brain Mapp.* 36, 3845–3866
50. Cardin, V. and Smith, A.T. (2010) Sensitivity of human visual and vestibular cortical regions to egomotion-compatible visual stimulation. *Cereb. Cortex* 20, 1964–1973
51. Eger, E. *et al.* (2015) Spatially invariant coding of numerical information in functionally defined subregions of human parietal cortex. *Cereb. Cortex* 25, 1319–1329
52. Gentile, G. *et al.* (2011) Integration of visual and tactile signals from the hand in the human brain: an FMRI study. *J. Neurophysiol.* 105, 910–922
53. Sereno, M.I. and Huang, R.S. (2014) Multisensory maps in parietal cortex. *Curr. Opin. Neurobiol.* 24, 39–46
54. Tudusciuc, O. and Nieder, A. (2007) Neuronal population coding of continuous and discrete quantity in the primate posterior parietal cortex. *Proc. Natl. Acad. Sci. U. S. A.* 104, 14513–14518
55. Guipponi, O. *et al.* (2013) Multimodal convergence within the intraparietal sulcus of the macaque monkey. *J. Neurosci.* 33, 4128–4139
56. Clery, J. *et al.* (2015) Impact prediction by looming visual stimuli enhances tactile detection. *J. Neurosci.* 35, 4179–4189
57. Schaafsma, S.J. and Duysens, J. (1996) Neurons in the ventral intraparietal area of awake macaque monkey closely resemble neurons in the dorsal part of the medial superior temporal area in their responses to optic flow patterns. *J. Neurophysiol.* 76, 4056–4068
58. Walsh, V. (2003) A theory of magnitude: common cortical metrics of time, space and quantity. *Trends Cogn. Sci.* 7, 483–488

59. de Hevia, M.D. and Spelke, E.S. (2009) Spontaneous mapping of number and space in adults and young children. *Cognition* 110, 198–207
60. Hurewitz, F. *et al.* (2006) Sometimes area counts more than number. *Proc. Natl. Acad. Sci. U. S. A.* 103, 19599–19604
61. Dakin, S.C. *et al.* (2011) A common visual metric for approximate number and density. *Proc. Natl. Acad. Sci. U. S. A.* 108, 19552–19557
62. Gebuis, T. *et al.* (2014) Topographic representation of high-level cognition: numerosity or sensory processing? *Trends Cogn. Sci.* 18, 1–3
63. Anobile, G. *et al.* (2016) Number as a primary perceptual attribute: a review. *Perception* 45, 5–31
64. Park, J. *et al.* (2016) Rapid and direct encoding of numerosity in the visual stream. *Cereb. Cortex* 26, 748–763
65. Bueti, D. and Walsh, V. (2009) The parietal cortex and the representation of time, space, number and other magnitudes. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 364, 1831–1840
66. Crollen, V. *et al.* (2013) A common metric magnitude system for the perception and production of numerosity, length, and duration. *Front. Psychol.* 4, 449
67. Meck, W.H. and Church, R.M. (1983) A mode control model of counting and timing processes. *J. Exp. Psychol. Anim. Behav. Process.* 9, 320–334
68. Van Opstal, F. and Verguts, T. (2013) Is there a generalized magnitude system in the brain? Behavioral, neuroimaging, and computational evidence. *Front. Psychol.* 4, 435
69. Balci, F. and Gallistel, C.R. (2006) Cross-domain transfer of quantitative discriminations: is it all a matter of proportion? *Psychon. Bull. Rev.* 13, 636–642
70. Chiou, R.Y. *et al.* (2012) Relative size of numerical magnitude induces a size-contrast effect on the grip scaling of reach-to-grasp movements. *Cortex* 48, 1043–1051
71. Cicchini, G.M. *et al.* (2016) Spontaneous perception of numerosity in humans. *Nat. Commun.* 7, 12536
72. DeWind, N.K. *et al.* (2015) Modeling the approximate number system to quantify the contribution of visual stimulus features. *Cognition* 142, 247–265
73. Sawamura, H. *et al.* (2002) Numerical representation for action in the parietal cortex of the monkey. *Nature* 415, 918–922
74. Dehaene, S. and Brannon, E.M. (2010) Space, time, and number: a Kantian research program. *Trends Cogn. Sci.* 14, 517–519
75. Diester, I. and Nieder, A. (2007) Semantic associations between signs and numerical categories in the prefrontal cortex. *PLoS Biol.* 5, e294
76. Fias, W. *et al.* (2003) Parietal representation of symbolic and nonsymbolic magnitude. *J. Cogn. Neurosci.* 15, 47–56
77. Piazza, M. *et al.* (2007) A magnitude code common to numerosities and number symbols in human intraparietal cortex. *Neuron* 53, 293–305
78. Bulthe, J. *et al.* (2014) Format-dependent representations of symbolic and non-symbolic numbers in the human cortex as revealed by multi-voxel pattern analyses. *Neuroimage* 87, 311–322
79. Bulthe, J. *et al.* (2015) Visual number beats abstract numerical magnitude: format-dependent representation of Arabic digits and dot patterns in human parietal cortex. *J. Cogn. Neurosci.* 27, 1376–1387
80. Damarla, S.R. and Just, M.A. (2013) Decoding the representation of numerical values from brain activation patterns. *Hum. Brain Mapp.* 34, 2624–2634
81. Cantlon, J.F. and Brannon, E.M. (2007) Basic math in monkeys and college students. *PLoS Biol.* 5, e328
82. Mantini, D. *et al.* (2013) Evolutionarily novel functional networks in the human brain? *J. Neurosci.* 33, 3259–3275
83. Dehaene, S. *et al.* (1999) Sources of mathematical thinking: behavioral and brain-imaging evidence. *Science* 284, 970–974
84. Grotheer, M. *et al.* (2016) Neuroimaging evidence of a bilateral representation for visually presented numbers. *J. Neurosci.* 36, 88–97
85. Shum, J. *et al.* (2013) A brain area for visual numerals. *J. Neurosci.* 33, 6709–6715
86. Tsao, D.Y. *et al.* (2003) Faces and objects in macaque cerebral cortex. *Nat. Neurosci.* 6, 989–995
87. Tsao, D.Y. *et al.* (2006) A cortical region consisting entirely of face-selective cells. *Science* 311, 670–674
88. Vanduffel, W. *et al.* (2014) Monkey cortex through fMRI glasses. *Neuron* 83, 533–550
89. De Martino, F. *et al.* (2017) The impact of ultra-high field MRI on cognitive and computational neuroimaging. *Neuroimage* http://dx.doi.org/10.1016/j.neuroimage.2017.03.060
90. Dumoulin, S.O. *et al.* (2017) Ultra-high field MRI: Advancing systems neuroscience towards mesoscopic human brain function. *Neuroimage* http://dx.doi.org/10.1016/j.neuroimage.2017.01.028
91. Huth, A.G. *et al.* (2016) Natural speech reveals the semantic maps that tile human cerebral cortex. *Nature* 532, 453–458
92. Grill-Spector, K. *et al.* (2006) Repetition and the brain: neural models of stimulus-specific effects. *Trends Cogn. Sci.* 10, 14–23
93. Larsson, J. *et al.* (2016) fMRI adaptation revisited. *Cortex* 80, 154–160
94. Kar, K. and Krekelberg, B. (2016) Testing the assumptions underlying fMRI adaptation using intracortical recordings in area MT. *Cortex* 80, 21–34
95. Kamitani, Y. and Tong, F. (2005) Decoding the visual and subjective contents of the human brain. *Nat. Neurosci.* 8, 679–685
96. Freeman, J. *et al.* (2011) Orientation decoding depends on maps, not columns. *J. Neurosci.* 31, 4792–4804
97. Freeman, J. *et al.* (2013) Coarse-scale biases for spirals and orientation in human visual cortex. *J. Neurosci.* 33, 19695–19703
98. Op de Beeck, H.P. (2010) Probing the mysterious underpinnings of multi-voxel fMRI analyses. *Neuroimage* 50, 567–571
99. Op de Beeck, H.P. (2010) Against hyperacuity in brain reading: spatial smoothing does not hurt multivariate fMRI analyses? *Neuroimage* 49, 1943–1948
100. Carlson, T.A. (2014) Orientation decoding in human visual cortex: new insights from an unbiased perspective. *J. Neurosci.* 34, 8373–8383
101. Wardle, S.G. *et al.* (2017) Edge-related activity is not necessary to explain orientation decoding in human visual cortex. *J. Neurosci.* 37, 1187–1196
102. Dubois, J. *et al.* (2015) Single-unit recordings in the macaque face patch system reveal limitations of fMRI MVPA. *J. Neurosci.* 35, 2791–2802
103. Naselaris, T. and Kay, K.N. (2015) Resolving ambiguities of MVPA using explicit models of representation. *Trends Cogn. Sci.* 19, 551–554
104. Sirotin, Y.B. and Das, A. (2009) Anticipatory haemodynamic signals in sensory cortex not predicted by local neuronal activity. *Nature* 457, 475–479
105. Logothetis, N.K. *et al.* (2001) Neurophysiological investigation of the basis of the fMRI signal. *Nature* 412, 150–157
106. Winawer, J. *et al.* (2010) Mapping hV4 and ventral occipital cortex: the venous eclipse. *J. Vis.* 10, 1
107. Caspers, S. *et al.* (2006) The human inferior parietal cortex: cytoarchitectonic parcellation and interindividual variability. *Neuroimage* 33, 430–448
108. Choi, H.J. *et al.* (2006) Cytoarchitectonic identification and probabilistic mapping of two distinct areas within the anterior ventral bank of the human intraparietal sulcus. *J. Comp. Neurol.* 495, 53–69
109. Scheperjans, F. *et al.* (2008) Probabilistic maps, morphometry, and variability of cytoarchitectonic areas in the human superior parietal cortex. *Cereb. Cortex* 18, 2141–2157
110. Holt, D.J. *et al.* (2014) Neural correlates of personal space intrusion. *J. Neurosci.* 34, 4123–4134

111. Wu, S.S. *et al.* (2009) Functional heterogeneity of inferior parietal cortex during mathematical cognition assessed with cytoarchitectonic probability maps. *Cereb. Cortex* 19, 2930–2945

112. Vanduffel, W. *et al.* (2001) Visual motion processing investigated using contrast agent-enhanced fMRI in awake behaving monkeys. *Neuron* 32, 565–577

113. Sunaert, S. *et al.* (1999) Motion-responsive regions of the human brain. *Exp. Brain Res.* 127, 355–370

114. Cottereau, B.R. *et al.* (2017) Processing of egomotion-consistent optic flow in the rhesus macaque cortex. *Cereb. Cortex* 27, 330–343

115. Colby, C.L. *et al.* (1993) Ventral intraparietal area of the macaque: anatomic location and visual response properties. *J. Neurophysiol.* 69, 902–914

116. Duhamel, J.R. *et al.* (1998) Ventral intraparietal area of the macaque: congruent visual and somatic response properties. *J. Neurophysiol.* 79, 126–136

117. Avillac, M. *et al.* (2005) Reference frames for representing visual and tactile locations in parietal cortex. *Nat. Neurosci.* 8, 941–949

118. Ishida, H. *et al.* (2010) Shared mapping of own and others' bodies in visuotactile bimodal area of monkey parietal cortex. *J. Cogn. Neurosci.* 22, 83–96

119. Okuyama, S. *et al.* (2015) Representation of the numerosity 'zero' in the parietal cortex of the monkey. *Sci. Rep.* 5, 10059