The Number Domain— Can We Count on Parietal Cortex?

Minireview

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Does the primate brain contain a dedicated and localized neural circuitry for processing generic numerical information? The human parietal cortex, particularly the intraparietal sulcus (IPS), has long been implicated in processing symbolic (verbal) number information. If the IPS is indeed the site of generic numerical processing, however, its neurons should also encode nonsymbolic numerosity information. Two recent studies by Shuman and Kanwisher and by Piazza et al. published in this issue of *Neuron* tested this assumption...with quite different results.

Symbolic counting and reckoning is a cultural achievement that coincided with or even caused progress in human civilization. The eminent importance of arithmetic in human culture captured the interests of neuroscientist early on. Could the brain host a dedicated neural circuitry that is specialized to process numbers? And if so, where would it be localized?

Neuropsychological studies in patients suffering from brain lesions historically provided the first evidence that certain counting and calculation processes may be located in specific regions of the brain. Besides the frontal lobe, the parietal lobe of the human cortex soon became a prime candidate for numerical competence. Patients with parietal lesions exhibited striking and often specific deficits in one or several counting and calculation tasks. With new noninvasive brain imaging techniques at hand, it became possible to explore number processing in intact brains. Using functional MRI and PET, two methods for detecting changes in brain metabolism and/or perfusion that are correlated with neuronal activity, the special role of the parietal cortex in number processing was confirmed. In the recent, best-controlled experiments, IPS activation was found to be due only to numerical processing, and not to other cognitive processes such as attention or task demand. Even more, parietal number activation was found to be automatic and independent of number notation (Naccache and Dehaene, 2001); segments of the IPS were activated regardless of whether numerals were spoken or written (Eger et al., 2003). In addition to functional MRI, the recent advances in the comparison of anatomical brain scans across subjects provided compelling evidence that developmental deficits in mathematical abilities correlate with a reduction of neural tissue in the (left) IPS (Isaacs et al., 2001).

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In summary, a central role of the human parietal cortex in symbolic number processing is evident. But juggling with number symbols is only one special case of numerical competence. It has been known for quite some time that nonlinguistic animals as well as preverbal human infants can discriminate the number of items or events based on nonverbal numerosity representations. And because fundamental characteristics of these nonverbal number representations are still present even in symbolic number representations, it is assumed that number symbols are mapped onto analog numerical representations during childhood. Thus, if the IPS is indeed the site of generic numerical representations, its neurons should encode not only symbolic numerals, but also nonsymbolic numerosity information. Two studies in this issue of *Neuron* tested this prediction using fMRI in human subjects. The answers given by these studies are quite clear-cut, but opposite in direction.

Shuman and Kanwisher (2004) (this issue of *Neuron*) explicitly tested the idea of a single localized and domain-specific system representing generic numerical information. They performed three different experiments to examine whether numerositiy activates the parietal lobe more than nonnumerical changes (color or shape) or task difficulty. Region of interest (ROI) analyses revealed that the IPS responded *less* strongly for numerosity than for closely matched color during the discrimination tasks, showed no fMRI-adaptation for numerosity, and responded more strongly to task difficulty per se. Shuman and Kanwisher's answer based on the negative results in all three tests is as simple as it is provocative: the parietal lobe is not specifically involved in representing nonsymbolic numerosity. As the authors note, their findings pose "a serious challenge to the hypothesis that a single, domain-specific parietal region underlies both symbolic and nonsymbolic number representation."

Fortunately, this challenge is immediately accepted by Dehaene's group. Piazza et al. (2004) (this issue of *Neuron*) independently tested fMRI adaptation with numerosities in humans, using a task design that is almost equivalent, and thus comparable, to Experiment 2 in the Shuman and Kanwisher paper. Subjects were repeatedly presented with several visual displays of a fixed numerosity (e.g., 16 dots), without the requirement to discriminate them. The rationale for fMRI adaptation to numerosity is this: if any brain region contains a population of numerosity-selective neurons that are tuned to a specific number of dots and automatically detect numerical information, such a population of detectors should habituate (i.e., decrease its discharge) with repeated numerosity presentations (Desimone, 1996). In this example, neurons tuned around numerosity 16 should habituate, while neurons tuned to other numerosities should be uninfluenced. Such a habituation effect was then "read-out" by recording the event-related fMRI activation to a single deviant numerosity presented at the end of a display sequence.

In striking contrast to Shuman and Kanwisher's report, Dehaene's group found that the only site of a whole-

brain search that significantly habituated to numerosity was the horizontal segment of the IPS. Importantly, no influence of item-shape change (used as nonnumerical control) was found. This part of the IPS is precisely the site where the neural instantiation of domain specificity for numerical information was predicted (Dehaene et al., 2003).

But what clearly distinguishes the study by Piazza et al. from most fMRI studies is the fact that it goes beyond a mere localization of function and provides insight into the neural mechanisms of numerosity coding in humans. By comparing blood oxygenation level-dependent (BOLD) activation to the habituation and deviant displays, the authors could detect systematic changes in activation as a function of the numerical distance of the deviant relative to the habituation numerosity. In other words, Piazza et al. were able to indirectly trace the average tuning curve of the underlying neural population. Such functions yielded (inverted) Gaussian tuning curves centered around the habituation numerosity. These fMRI tuning curves were slightly broader but otherwise comparable to behavioral numerosity discrimination performance curves measured in the same study. Piazza et al. were even able to link the convergence of behavioral and imaging data by mathematical modeling, thus adding a third, theoretical level of analysis.

It is intriguing to see how the properties of these fMRI tuning curves are more or less identical to the tuning curves of single numerosity-selective neurons in the primate prefrontal and posterior parietal cortex (Nieder et al., 2002; Nieder and Miller, 2004). In both species and signal types, the tuning curves show a Weber-fraction signature, meaning that the tuning width (i.e., the precision of the representation) decreases linearly with set size. In addition, and like single-cell data (Nieder and Miller, 2003), fMRI tuning curves seem to be well described on a logarithmic scale (or "number line," respectively), even though the difference between linear and logarithmic scaling did not reach significance in humans.

Overall, the novel data by Piazza et al. provide strong evidence that the analog magnitude system used to detect nonsymbolic numerical information may indeed constitute the evolutionary precursor system for elementary arithmetic: the analog magnitude system is found in both human and nonhuman species, numerosity selectivity is relatively overrepresented at comparable brain regions (namely in the IPS), and both systems share fundamental tuning properties. To establish an even stronger case for a precursor system, one would preferably like to know whether numerical information in dot displays is also extracted automatically in the monkey brain (i.e., without having the monkey discriminate numerosities). Furthermore, it would be extremely interesting to see whether numerosity is coded for both simultaneously as well as sequentially presented items in both human and monkey, ideally even across modalities.

With the articles from two internationally renowned functional imaging laboratories, we have a striking example that almost identical paradigms can produce quite contrary results and conclusions. Since there is no reason to doubt that both studies have been performed at the highest possible standards, we need to decide what we learn from these articles. Are there dedicated numerosity-selective neurons in the IPS of the human brain or not? These contrasting results leave us with two general and important questions. First, what does a failure to detect significant fMRI activation during a particular task indicate? Second, how reasonable are notions about localization and domain specificity with respect to the brain? Far from being able to provide a definite solution to those problems, a few thoughts may be helpful for further discussion.

Since fMRI is based on relative changes in blood oxygenation between different conditions, the interpretation of a failure to detect BOLD activation—as in the paper by Shuman and Kanwisher—may not be as straightforward as it seems. The authors emphasize that such a failure can not be regarded as "null result" because they were very well able to replicate IPS activation reported by another influential paper from Dehaene's group (Dehaene et al., 1999). However, fMRI detects a continuous mass signal that needs to be smoothed and averaged over a relatively large tissue volume and time frame (at least compared to single-cell recordings) and even across subjects. Several cubic millimeters of brain tissue most likely harbor more than one neural network, and such networks may be specialized but partly overlapping or intermingled (Pinel et al., 2004; Kleinschmidt, 2004) so that they cannot be dissociated spatially or temporally by the relative macroscopic resolution of fMRI. For example, recordings in monkeys showed that only some 10%–20% of all IPS neurons are selective to visual numerosity (Nieder and Miller 2004); necessarily, the remaining 80%–90% of neurons in this region must be engaged in different functions. In the parietal lobe, numerosity-selective neurons are most abundant in the fundus of the IPS (Nieder and Miller, 2004), but the ventral region of macaque IPS is also discussed in being involved in cross-modal attention, coding heading direction, or controlling defensive movements (Cooke et al., 2003). Moreover, a special neural circuitry may even be engaged in several tasks, forming adjustable neural ensembles according to different requirements. This is particularly problematic for the most flexible neural networks guiding executive functions, as in the prefrontal cortex. Interestingly, the prefrontal cortex showed the highest proportion of selective neurons in a numerosity discrimination task (Nieder and Miller, 2004). Such neuronal numerical representations may not be established automatically (as seems to be the case in IPS), but they are nevertheless genuine and absolutely necessary for the monkey's behavior. Together, certain brain regions might indeed play a crucial role in processing numerical information, but their blood flow may not be significantly modulated on average for the reasons mentioned above.

This leads to the second question. If the above-mentioned neuronal scenario is true, and only some 10%–20% of all neurons recorded in a given area are task selective, one may of course argue that it is not justified to talk of a domain specificity, and this is exactly what Shuman and Kanwisher conclude based on their negative results. However, what does "domain specificity," "localization," and "modularity" mean from a neurophysiological point of view?

The idea of "modularity of mind" (MOM) is a psychological concept that became very influential in cognitive science (Fodor, 1983). While MOM turned out to be ex-

tremely inspiring for studying the mind, the question is whether MOM can be easily and gainfully transferred to the neural substrate of the mind, the brain. This transfer from the mental to the neural level seems to cause major confusion.

According to Fodor's influential concept, certain psychological processes are modularly organized ("modules," sometimes also termed "mental organs"). Two defining characteristics of modules (among others) are "localization" and "domain specificity," the two main aspects refuted or defended in the current discussion about the processing of numerical information. Is the number system domain specific, and is it localized in a certain area of the brain? (It may be important to bear in mind that while modules need to be domain specific and localized according to Fodor, it does not follow that domain specificity needs to be localized. In many discussions about a putative number domain, however, it is implicitly assumed that such a domain also has to be localized.)

Shuman and Kanwisher's argumentation is geared to test a strong type of domain specificity including localization. If a number module exists, they say, it should deal exclusively with a single type of information, namely numerical information (whether it be symbolic or nonsymbolic), and it should be localized in a restricted brain region. How realistic is such a claim? A look at another seemingly domain-specific process, namely face recognition, may be instructive. In humans, face perception is thought to be carried out by domain-specific mechanisms, that is, by modules specialized for processing faces in particular (Kanwisher, 2000). Based on fMRI studies, it was found that humans seem to have a special brain region in the ventral temporal cortex ("fusiform face area") that processes faces and only faces. A recent fMRI study in monkeys (Tsao et al., 2003) revealed face-selective cortical patches concentrated in the caudal part of the inferior temporal cortex, very reminiscent of face-selective patches in humans. Thus, based on functional imaging, both primate species seem to have specialized and localized cortical areas that are domain specific for faces. The puzzling aspect, however, is that such strong BOLD signals in the macaque were found even though single-cell physiologists have reported a maximum of only 20% of face-selective cells in different parts of the temporal lobe over the last decades. This discrepancy in face processing raises issues about the relationship between BOLD signals and single-cell physiology (Tsao et al., 2003), but also about the meaning of localized domain specificity in the brain. The temporal lobe may rather process faces and other categories in a topographically overlapping and distributed fashion (Haxby et al., 2001). The very same issues have to be addressed in parietal lobe in the context of number processing. Neurons encoding numerical or magnitude information may be intermingled and distributed along the IPS, with local changes in density causing shifts in peak activation when measured with fMRI (Pinel et al., 2004). A "modularity of mind" may be well justified, but a "modularity of brain" may not.

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