Comparison of Quantities: Core and Format-Dependent Regions as Revealed by fMRI

Philippe Chassy1 and Wolfgang Grodd2

1Institute of Medical Psychology and Behavioral Neurobiology, Faculty of Medicine, University Hospital Tübingen, 72076 Tübingen, Germany and 2Klinik für Psychiatrie und Psychotherapie, Universitätsklinikum Aachen, D-52074 Aachen, Germany

Address correspondence to Philippe Chassy, Institute for Medical Psychology and Behavioral Neurobiology, University Hospital Tübingen, 29 Gartenstrasse, Office 309, 72076 Tübingen, Germany. Email: philippe.chassy@medizin.uni-tuebingen.de.

The perception and handling of numbers is central to education. Numerous imaging studies have focused on how quantities are encoded in the brain. Yet, only a few studies have touched upon number mining: the ability to extract the magnitude encoded in a visual stimulus. This article aims to characterize how analogue (i.e., disks and dots) and symbolic (i.e., positive and negative integers) formats influence number mining and the representation of quantities. Sixteen adult volunteers completed a comparison task while we recorded the blood oxygen level-dependent response using functional magnetic resonance imaging. The results revealed that a restricted set of specific subdivisions in the right intraparietal sulcus is activated in all conditions. With respect to magnitude assessment, the results show that 1) analogue stimuli are predominantly processed in the right hemisphere and that 2) symbolic stimuli encompass the analogue system and further recruit areas in the left hemisphere. Crucially, we found that polarity is encoded independently from magnitude. We refine the triple-code model by integrating our findings.

Keywords: IPS, mathematical cognition, number, visual perception

Introduction

Due to its central role in the development of mathematical abilities, the number sense has generated much research. Overall, the intraparietal sulcus (IPS) in both hemispheres is believed to play a key role in coding quantities (Nieder and Dehaene 2009). Numerous functional magnetic resonance imaging (fMRI) studies have consistently shown that the IPS is involved in magnitude processing regardless of the type of task (McNeil and Warrington 1994; Van Harskamp and Cipolotti 2001; Zago et al. 2001; Zhou et al. 2007; Ischebeck et al. 2009) and irrespective of format (Eger et al. 2003; Fias et al. 2003). Furthermore, in a study on nonhuman primates, Nieder and Miller (2004) have demonstrated that single neurons in the IPS display magnitude-dependent activity. The question of magnitude representation has thus been intensely investigated during the past decades. However, much less is known about how the quantity is extracted from various types of visual displays. The process of quantity extraction, which we term number mining, is a necessary step prior to any further mathematical processing. Several research groups primarily interested in how a quantity is encoded in the IPS have touched upon the number mining problem (Fias et al. 2003; Lammertyn et al. 2003; Venkatraman et al. 2005; Cohen Kadosh et al. 2007; Piazza et al. 2007). These studies have yielded a complex, and sometimes conflicting, pattern of results that is difficult to integrate into a unique theory. The present article aims at qualifying the different routes that serve number mining and at determining whether magnitude representation depends up on number mining.

Previous literature has introduced a distinction between the numerical processing of analogue and symbolic stimuli (Dehaene and Cohen 1997; Fias et al. 2003; Lammertyn et al. 2003; Venkatraman et al. 2005; Piazza et al. 2007; Holloway et al. 2010). Whereas in an analogue stimulus the magnitude is a perceptually accessible aspect of the stimulus, in a symbolic stimulus the magnitude being coded is independent from physical characteristics. For example, 3 dots and the Arabic digit “3” both implement the notion of 3 but the visual codes differ drastically. Although analogue and symbolic visual signals may utilize the same brain areas for representing magnitudes, they most likely will utilize different routes for number mining. To identify regions that are responsive to both analogue and symbolic stimuli, Fias et al. (2003) requested participants to compare either numbers or nondiscrete quantities. Their analysis identified the left IPS as the center of a network responsive to magnitude. Rather than focusing on common regions, Venkatraman et al. (2005) used an arithmetical task to reveal the areas that respond differentially when participants process digits or dots. They found that the processing of digits activated areas that are more lateralized to the left. Recently, Holloway et al. (2010) asked participants to compare digits or dots in arrays and found that the posterior region of the right superior parietal lobule (SPL) was more responsive for dots. Since these studies involved different tasks and types of stimuli, it is difficult to draw a definite conclusion on how the brain extracts magnitudes from various types of visual display. Yet, by revealing format-dependent processing, these studies opened the door for number mining considerations.

Within the analogue category, we distinguished the stimuli coding for approximate magnitudes (e.g., object size) from those coding for exact quantities (e.g., dots). This distinction between an approximate and an exact number sense is grounded on clinical studies (Dehaene and Cohen 1991; Lemer et al. 2003) and was confirmed by neuroimaging experiments (Piazza et al. 2006; Kucian et al. 2008). For example, Piazza et al. (2006) asked adult participants to perform an estimation and a calculation task. The results corroborated the distinction by showing that approximate processing was represented by a right lateralized network, while exact processing predominantly recruited areas in the left hemisphere. These results were echoed by developmental studies showing that the acquisition of notion of exact quantities modifies the activity pattern of number processing (see Halberda and Feigenson 2008 for behavioral data; Cantlon et al. 2010 for an fMRI demonstration). Finally, research convincingly shows that the processing of quantities in the IPS is inherited from animals (see Nieder 2005 for a review). Hence, one purpose of the present study was to explore how the inherited number system
handles quantities that are coded in approximate and exact formats.

With respect to the processing of symbolic stimuli, we distinguished between the symbolic representation of positive (e.g., 3) and negative integers (e.g., –3). The latter were introduced as a more abstract level of numerical conceptualization. Even though negative integers have not attracted as much attention as positive integers, they are a valid option to study abstract quantities. Based on behavioral evidence, Fischer (2003) and Shaki and Petrusca (2005) have convincingly argued in favor of negative numbers as being mapped in a spatial code. Based on this evidence, we expected negative numbers to activate the IPS. Also, that negative integers are rooted in the same system than positive integers will enable exploring the influence of the notion of negativity. To address this issue, 2 behavioral studies compared the processing of negative and positive numbers (Ganor-Stern and Tzelgov 2008; Tzelgov et al. 2009). Their results provide evidence that polarity is independently coded from magnitude, which suggests that additional neural networks might be in charge of encoding the notion of negativity. As negative integers do not visually differ substantially from positive integers, we do not expect differential activations in primary visual areas. But as negative integers represent a more abstract numerical concept, we hypothesized that processing would recruit the IPS and an additional region coding for negativity. To the best of our knowledge, until now no imaging study has compared the neural correlates of positive and negative integers.

In line with the literature, the experiment was designed with 4 classes of visual stimuli: 2 classes belonging to the analogue class (i.e., approximate and exact) and 2 classes belonging to the symbolic class (i.e., positive integers and negative integers). Each type of stimuli implemented a different way to code a magnitude.

Materials and Methods

Participants
To minimize the potential number of confounding variables, several factors have been controlled during the selection of the participants. As handedness may affect the lateralization of functional brain areas (Szaflarski et al. 2002), we selected only right-handed individuals. As evidence exists that males and females might differ in their approach to mathematical processing (Keller and Menon 2009) and that numerical processing differs between children and adults (Kucian et al. 2008), we consequently limited the study to male adults.

fMRI data were acquired from 16 right-handed male volunteers (age: mean = 28.62 years-old, standard deviation = 5.75 years-old) while they were performing a comparison task. All participants had normal or corrected-to-normal vision and reported no history of neurological or psychiatric illness. The participants were paid €15 per hour for their participation. Before giving written informed consent, all participants were informed of safety issues and of the aim of the study. The study was approved by the ethics committee of the University Hospital of Tübingen.

Task
The comparison task has been used to elicit magnitude-specific activation in the IPS (Zorzi et al. 2011). Because of its robustness, and since it includes no arithmetical processing, the comparison task constitutes a good candidate to examine number mining and the IPS (Zorzi et al. 2011). Because of its robustness, the comparison task has been used to elicit magnitude-specific activation in the IPS (Zorzi et al. 2011) while they were performing a comparison task. All participants had normal or corrected-to-normal vision and reported no history of neurological or psychiatric illness.

Stimuli and Procedure
Four types of stimuli were used (see Fig. 1, left panel): disks (9 different radii), number of dots (from 1 to 9), positive integers (range from 1 to 9), and negative integers (range from –1 to –9). The dots were randomly assigned to a 3 × 3 canonically arranged matrix (similar to Piazza et al. 2002). For each condition, 24 pairs of stimuli were randomly generated. Laterality was controlled by presenting the bigger magnitude half of the time (50%) in the right and half of the time (50%) in the left visual hemifield. The stimuli pairs were then distributed randomly in separate blocks with the constraint that a block was made of only 1 type of stimuli (see Fig. 1, right panel).

A trial consisted of a 1.8-s display of a pair of stimuli. The stimuli were presented at equal eccentricities from a central fixation point (invisible to the participant). The stimuli were followed by an intertrial interval of 0.2 s in which a fixation cross was presented. A sequence of 8 trials with 1 stimulus type constituted a block. There were 3 blocks for each experimental condition. A complete run was made up of the 12 blocks with interleaved resting periods of 14 s. The run started and terminated on a resting period of 14 s. The 12 blocks were randomly distributed within a run with the restriction that 2 blocks of the same category could not be presented successively.

Prior to the start of a block, a cue word displayed for 2 s informed the participant whether to compare disk size, the number of dots, positive integers, or negative integers. Before the participants entered the scanner, they practiced with 2 blocks for each category of stimuli. This procedure enabled the experimenter to check that the participant understood the task and helped the participant familiarizing with the task.

Apparatus and fMRI Data Acquisition
All participants were scanned in the Section of Experimental MRI of the Central Nervous System at the Department of Neuroradiology of the University Hospital Tübingen, Germany. Structural and functional images were acquired using a whole-body 3-T Siemens Trio scanner equipped with a 32-channel head coil (Siemens, Erlangen, Germany). Participants were positioned head first and supine in the bore. Anatomical data were collected with a magnetization prepared rapid gradient echo sequence (time echo [TE] = 292 ms, time repetition [TR] = 2300 ms, flip angle = 8°, field of view [FoV] = 256 × 256 mm, 176 slices, 1-mm thickness). After the anatomical map, a magnetic field map was acquired to correct for inhomogeneities of the static magnetic field. Functional images were acquired using a gradient echo planar imaging T2* sequence sensitive to blood oxygen level-dependent (BOLD) signal with the following parameters: TE = 30 ms, TR = 2000 ms, flip angle = 90°, FoV = 192 × 192 mm, matrix size = 64 × 64. Thirty-two slices were acquired with a thickness of 3.2 + 0.8 mm gap resulting in voxels with the resolution of 3 × 3 × 4 mm³.

fMRI Data Analysis
Standard preprocessing procedures were performed using Statistical Parametric Mapping (SPM, version 8, Wellcome Trust for Neuroimaging, University College London). The first 5 volumes of each run were discarded to allow for T1 equilibration. By using the magnetic field map, each volume was corrected for magnetic field inhomogeneities. All functional volumes were then realigned to the first volume of the session and corrected for head motion. The functional mean image was coregistered to the anatomical image. Functional images were additionally normalized to the Montreal Neurological Institute (MNI)
standard template. During normalization, the functional volumes were resampled to a 5 × 3 × 3-mm³ resolution. Last, functional images were smoothed using an isotropic Gaussian kernel (full-width at half-maximum = 8 mm).

Functional data were subjected to a general linear model analysis as implemented in SPM8. To model the response of each subject, we used 4 conditions: disk sizes, arrays of dots, positive integers, and negative integers. For each condition, the canonical hemodynamic response function (cHRF), the time derivative, and dispersion derivative were calculated. The cHRF models the most commonly observed response of the BOLD impulse. The time derivative function accounts for signal responses that are up to 1 s earlier (or later) than the cHRF. Similarly, the dispersion derivative indicates if the peak lasts less or longer than usual. The calculation of these additional parameters allows a better modeling of the BOLD response (Henson et al. 2001). To control for motion, the 6 motion parameters were entered as regressors of no interest.

To generate the basic activation maps, baseline activity was subtracted from task conditions. Hence, the first step of the analysis yielded 4 basic activation maps: 1) disk size versus baseline (disk), 2) arrays of dots versus baseline (dots), 3) positive integers versus baseline (positive), and 4) negative integers versus baseline (negative). These contrasts reflect the brain areas in charge of dealing with number mining, number comparison, planning, and execution of the response. The basic activation maps were then used to examine how stimulus format influences neural processing.

To qualify the components common to all routes, first a conjunction analysis of all 4 basic activation maps (disk ∩ dots ∩ positive ∩ negative) was performed. To identify regions that are commonly activated by analogue stimuli, a disk ∩ dots conjunction analysis was applied. To establish which regions are differentially active, we computed the contrast between the 2 classes of analogue stimuli (dots > disk). Both the conjunction and contrast activity maps were then used to identify regions that are in charge of computing approximate (disk) and exact quantities (dots).

A similar procedure was applied for the 2 types of symbolic stimuli: we generated a conjunction (negative ∩ positive) and a contrast activation map (negative > positive). These maps were used to identify the symbolic pathway and, more specifically, to assess how the level of abstraction of the mathematical quantity influences number mining. In a last step, the analogue stimuli on the one hand and symbolic stimuli on the other hand were merged. Both categories were compared [(disk + dots) > (positive + negative)] to detect the areas that are differentially activated during the processing of analogue and symbolic stimuli.

Unless stated otherwise, both first- and second-level analysis of significant clusters of activation were determined using a voxel-level statistical threshold of \( P < 0.0001 \) uncorrected with a spatial extent threshold of \( k = 5 \). For conjunction analysis, only clusters of a size larger than 10 voxels exhibiting a corrected familywise error at \( P < 0.05 \) are reported. The activated brain regions were assigned according to the anatomical toolbox (Eickhoff et al. 2005, version 1.7b, anatomical update 2010). Cerebellar activations were not considered due to incomplete coverage of the cerebellum in most of the subjects.

**Figure 1.** (Left) Examples of stimuli used for the 2 analogue and the 2 symbolic conditions. (Right) Time course of events in a run: blocks of 16 s (8 trials) were alternating with resting periods of 14 s.

### Results

**Behavioral**

Mean performance was calculated by dividing the number of correct responses by the total of responses. Figure 2 shows the mean response time (RT) and performance of the participants for each experimental condition. As expected, all subjects performed with high accuracy (mean = 97.22%, standard error [SE] = 1.58%).

Mean performance and RTs for each participant were computed for each condition (disk, dots, positive, and negative) and laterality of the correct responses (right vs. left). A repeated-measures analysis of variance performed with format and laterality as within-subjects factors and average performances as the dependent variable yielded no significant main effect (format: \( F_{3,45} = 1.24, P = 0.31 \), mean squared error [MSE] < 0.01; laterality: \( F_{1,15} = 0.25, P = 0.62, \text{MSE} = 0.02 \)) and no interaction (\( F_{3,45} = 1.00, P = 0.40, \text{MSE} < 0.01 \)). For the RT analysis, all error trials were discarded. Response latencies larger than 1800 ms or smaller than 200 ms were also excluded from the analysis (0.1% of the total sample). Due to equipment failure, behavioral data of 1 participant were not available for the last run. The average RT was calculated for each participant and entered into a repeated analysis of variance with format (disk, dots, positive, and negative) and laterality (left vs. right) as within-subjects factors (see Fig. 2). Laterality did not significantly influence the RTs (\( F_{1,15} = 0.39, P = 0.54, \text{MSE} = 0.01 \)). Visual format significantly affected the RTs of the participants (\( F_{3,45} = 78.11, P < 0.01, \text{MSE} < 0.01 \), with significant shorter RTs for dots compared with all other conditions. The mean RTs were as follows: disk, 0.68 s (SE = 0.02 s); dots, 0.58 s (SE = 0.02 s); positive, 0.65 s (SE = 0.02 s); and negative, 0.69 s (SE = 0.02 s). The Format × Laterality interaction was not significant (\( F_{3,45} = 1.47, P = 0.24, \text{MSE} < 0.01 \)).

**fMRI Results**

Figure 3 presents the results of the 4 basic activation maps: disk, dots, positive and negative maps. In all 4 conditions, various visual areas along the dorsal (including the bilateral SPL) and ventral streams were activated, showing that an appreciable number of cortical areas are involved in number mining (Supplementary Table 1). More specifically, disk comparison yielded a pattern with increased BOLD signal in the right middle occipital gyrus, left V5, and bilaterally in the superior parietal lobules and precentral gyri. A decrease in the BOLD signal was found in the right precentral gyrus, left...
angular gyrus, middle cingulate cortex, and the cuneus. The dots contrast revealed increased activation in the right and left superior parietal lobules together with the right insula and precentral gyrus. Deactivation occurred in the right angular gyrus, Rolandic operculum, middle cingulated cortex, and the cuneus. Positive integers generated a bilateral activation of the superior parietal lobules and a deactivation in the left angular gyrus and the anterior part of the medial temporal gyri. The
comparison of negative integers yielded a similar pattern of activation except for an additional activation in the left V5 and a deactivation in the anterior parts of the temporal lobe.

The cortical areas that exhibit a significant BOLD signal change in all task conditions are revealed by the conjunction analysis of the 4 basic contrasts (see Fig. 4A). The analysis confirms that comparing magnitudes involves a large network comprising low-level visual areas (right BA17), high-level visual areas (left occipital gyrus), and numerical centers in the right IPS. Two peak activation sites were located in the horizontal segment: one in hIP3 (MNI: 30, -51, 48) and one in hIP2 (MNI: 45, -39, 45). The execution of the behavioral response has generated a left-dominant motor activation cluster that peaked in BA6.

To examine the regions that are active during the processing of analogue stimuli, a conjunction analysis was performed with the disk and dots conditions (Fig. 4B). The analysis revealed a network involving the Rolandic operculum, rectal gyrus, and middle occipital gyrus in the left hemisphere, and the middle orbital and supramarginal gyrus in the right hemisphere (see Fig. 4B). Paralleling the activation map yielded by the conjunction of all 4 conditions, the conjunction of analogue conditions revealed a bilateral activation of visual cortices. We also note the activation of a huge, motor-related activation cluster that peaks in the left precentral gyrus and extends to the supplementary motor area. Finally, localized sites of activation were spotted in the postcentral gyrus (i.e., somatosensory areas). These cortical areas are known to process somatosensory or motor information and as such are not of central interest in examining number mining. The dots > disk contrast presented in Figure 4C revealed clusters of activation

Figure 4. (A) Activation map resulting from the conjunction analysis including the 4 experimental basic contrasts. This contrast reveals the areas that were active in all conditions and thus putatively play a central role in any task involving a comparison between quantities. (B) Activation map of the conjunction analysis of the 2 analogue conditions (i.e., disk and dots). This contrast reveals the core areas that constitute the inherited number system. (C) Dots > disk contrast. It reveals the elements that are the most fundamental to number mining and processing. (D) The conjunction of negative integers (NI) and positive integers (PI). It reveals the areas that are engaged in symbolic processing regardless of the level of abstraction of the mathematical entity being processed. (E) The NI > PI contrast reveals the area in charge of coding the notion of negativity. (F) The analogue > symbolic contrast shows the regions that are involved in extraction of visually coded quantities.
in the bilateral primary visual cortices (BA17), the right superior parietal lobule, and the bilateral middle occipital gyri. Crucially, the ventral part of left visual area 3 (i.e., left hOC3v) was sensitive to both the chRF and its time derivative, supporting the view that this region was more responsive in the dots condition than in the disk condition and peaks earlier than predicted by the canonical response.

The conjunction analysis of both symbolic conditions yielded an interesting pattern of activation (see Fig. 4E). The left motor-related BA6 areas, the right hIP3, and superior parietal lobule were more active when the participants were performing numerical comparison than at rest. Contrasting the 2 symbolic conditions (negative > positive) highlighted significant activation in the right superior orbital gyrus. The time derivative contrast revealed significant clusters of early activation in the left SPL (Fig. 4F).

To distinguish the regions that belonged to the symbolic path from those belonging to the analogue path, the 2 analogue conditions were contrasted with the 2 symbolic conditions (disk ∩ dots) - (positive ∩ negative). The contrast (Fig. 4F) reveals that the bilateral BA17 was more active during the processing of analogue stimuli. The right inferior parietal cortex and the right inferior temporal gyrus also show higher activation for the analogue stimulus. It is worth noting that the opposite contrast (i.e., symbolic > analogue conditions) does not yield significant results.

The contrast estimates at the sites of peak activation provide further information on number mining and retention. The disk ∩ dots conjunction peak is located in the right superior parietal lobule (MNI: 24, −63, 51). Noticeably, according to the probability map (Eickhoff et al. 2005; software update 2010), this site has a 20% chance of belonging to hIP3. The contrast estimates at this location (Fig. 5A) show that the site is more active in both conditions than at rest. As shown in Figure 5B, the contrast estimates of dots > disk at this location (MNI: 24, −63, 51) revealed that the BOLD signal is adequately modeled by the chRF and its time derivative (see the bar graph in Fig. 5B). A similar procedure for the activity peak in the left superior lobule (MNI: −24, −60, 51) reveals that this spot is active in both symbolic conditions (Fig. 5C) and does activate faster when participants had to compare negative integers (Fig. 5D; statistics at α = 0.001, k > 5). With respect to the conjunction analysis of all conditions, the contrast estimates at the peak site (MNI: 30, −51, 48) of the cluster indicate that the hIP3 region (at MNI: 30, −51, 48) is significantly more active in all conditions compared with baseline (see bar graph in Fig. 5E). As shown in Figure 5E, the activity in this site is appropriately modeled by the chRF.

**Discussion**

The aims of our study were to characterize the various routes that extract the magnitude in visual displays and to understand how this process influences the encoding in the IPS. A comparison task was used to assess how participants compare magnitudes encoded in 4 different formats. In line with previous studies, we used disks and dots as analogue stimuli, and positive integers as symbolic stimuli. We introduced negative integers to examine the coding of abstract mathematical concepts (i.e., negativity). It was expected that the right IPS, as the repository of the number sense, should be activated in all conditions. With respect to semantic assignment, the activation foci for each category should be located in distinct regions: we expected right IPS activation for analogue stimuli and a bilateral IPS activation for symbolic stimuli.

The discussion is divided in 4 sections. First, we discuss the comparison of analogue stimuli as the findings show how exact and approximate magnitudes are extracted. We discuss in the second section the comparison of symbolic stimuli. It reveals the neural networks that process numbers in symbolic format, including abstract mathematical notions such as negativity. In the third section, the commonalities of and differences between analogue and symbolic stimuli will be synthesized. In the last section, we integrate our findings into the triple-code model from Dehaene et al. (2003).

**Analogue Routes**

The analogue route is primarily characterized by the brain structures that were active in both analogue conditions. The conjunction analysis showed that several subparts (hIP2 at MNI: 45, −39, 45; hIP3 at MNI: 30, −51, 48) of the right IPS are consistently active in both conditions. This result is in line with the study by Piazza et al. (2002) that reported a similar right-dominant pattern of activation in the parietal cortex when participants compared arrays of dots. Our finding supports the idea that the neural signals coding magnitude are held in a specific subpart of the IPS. The activation of the left Rolandic operculum indicates verbal processing and thus suggests that human agents automatically access a verbal code. There is, however, a possibility that activation of the left Rolandic operculum may merely reflect subvocalization. Our results are consistent with the triple-code model (Dehaene et al. 2003) and locate with higher precision where the information about magnitude is encoded.

The contrast dots > disk highlights the areas that are specific to code exact quantities. The contrast shows that not only the left middle occipital gyrus but also the ventral part of left area V3 (hOC3v) is more active in the dots than in the disk condition. hOC3v is a retinotopic region belonging to the ventral stream (Rottschy et al. 2007), and as such, one might suggest that the analogue route relies partly on verbal coding. However, the ventral V3 region is usually not thought to be part of the network that is connected to the visual word area (McCandliss et al. 2003). Furthermore, in monkeys this region projects onto the middle temporal area (Lyon and Kaas 2001) showing that it can modulate spatial processing. As hOC3v activation has been shown to merely reflect top-down controlled attention (Lauritzen et al. 2009), we suggest that the differential activation is accounted for by the increase in attentional resources needed to estimate the number of dots. The differential activity of right V1 (BA17) also reflects spatially driven attention (Proverbio et al. 2010). hOC3v and right V1 are part of the number mining system as their activation is dependent upon the format of the visual input.

The central finding of the contrast between the 2 analogue conditions is that the right superior parietal lobule is more active in the dots than in the disk condition. This finding suggests that this area is more involved in the comparison of exact quantities (i.e., number of dots). Our results are consistent with the idea that the route taken by approximate and exact signals will eventually terminate in the right IPS. A neurophysiological explanation is that simple accumulator neurons are sufficient to explain comparison of approximate
quantities, while accumulator-tuned neurons are necessary for the comparison of exact numbers. Our conclusions are consistent with previous research about the distribution of numerical-sensitive neurons in the right parietal cortex and with current models of number processing (Dehaene and Changeux 1993; Piazza and Izard 2009).

**Symbolic Routes**

The main finding yielded by the conjunction analysis is that the right IPS (hIP3) and superior parietal lobule were significantly active. The time derivatives further specify that these 2 regions were fast in responding to stimulus presence. These results again highlight the central role that the right hIPS plays in the number sense.
When we contrasted the activity maps generated by the comparison of negative and positive digits, we found a significant difference in the right BA17. Contrary to our prediction, the early visual areas were significantly more activated by the additional presence of a minus sign. This difference in activation may be accounted for by enhanced spatial attention (Proverbio et al. 2010). In addition, the contrast revealed that the left SPL was more active in the negative condition (see Fig. 5E). This finding is crucial regarding the debate about the brain structures implicated in the processing of abstract mathematical knowledge. Our results suggest that the notion of negativity is implemented in a restricted zone that lies close to a cortical site where positive numbers (left IPS) are mapped onto spatial codes (right IPS). This interpretation is supported by various strands of research. First, our results are consistent with developmental studies showing that the left IPS is progressively recruited during the learning of mathematical symbols (Cantlon et al. 2006, 2010). Second, adults performing a subtraction task, which obviously includes the notion of negativity, activate the left superior parietal lobule (Simon et al. 2004). In addition, when adults react to potential money losses, their left superior parietal module is particularly responsive (De Pascalis et al. 2010). Finally, our view is in line with the cultural recycling hypothesis (Dehaene and Cohen 2007), which states that cultural acquisition of mathematical abilities needs a neural niche close to language processing areas. Our findings are consistent with the pool of available data suggesting that the left superior parietal lobule is a core neural module in representing negativity. In short, both symbolic stimuli include the right hIP3 as a terminal representation of magnitudes, but they make a differential use of the neural networks in the left superior parietal lobule.

**The Common System**

The conjunction analysis of all conditions (see Fig. 5A) revealed a right lateralized network including key elements in the right IPS and in the right superior parietal lobule (MNI: 30, –60, 54). These results basically replicate what has been previously found in quantity comparison tasks: Regardless the format of the stimuli, the IPS will eventually code the quantities being compared (Pinel et al. 2001; Piazza et al. 2002; Cohen Kadosh et al. 2005; Holloway et al. 2010). In addition to this predictable result, the conjunction analysis revealed further specific information about the localization of the core parts of number processing. Due to advances in the precision of the anatomical atlases (Eickhoff et al. 2005, software update 2010), we were able to identify localized activation within 2 subregions of the right IPS: namely, hIP2 (MNI: 45, –39, 45) and hIP3 (MNI: 30, –51, 48). The central module of magnitude representation is in our view a neural network recruiting neurons in the hIP2 and hIP3 regions. In contrast with Wu et al. (2009), we did not find activation in hIP1. Since we also used probabilistic cytoarchitectonic maps, it is unlikely that the difference in pattern of activation is due to the type of analysis. Rather, considering the fact that Wu et al. (2009) used arithmetic operations, we would suggest that hIP1 is somehow involved in the mixing of the magnitude values. For example, it might hold the result of an addition in a spatial format. We note that hIP2 was active in the conjunction of all 4 conditions (MNI: 45, –39, 45), but that it did not constitute a zone of peak activity when the conjunction was limited to the symbolic conditions (i.e., positive & negative). These results suggest that the mapping of the analogue representation of quantities recruits the right hIP3 but not the right hIP2. We further suggest that hIP2 houses accumulator cells (similar to the accumulator cells found in monkey; see Roitman et al. 2007); the cells in hIP3 would be accumulator cells tuned to respond to specific values. Our theoretical conclusion is that symbols are mapped directly into these hIP3 cells.

The left angular gyrus was deactivated in all 4 conditions. This finding is consistent with previous studies addressing related issues (see Ischebeck et al. 2009 for an example and a discussion). According to the triple-code model, the angular gyrus is implicated in the retrieval of mathematical facts (Dehaene et al. 2003). In the present experiment, there was no need to retrieve mathematical facts so that this region was not required. Basically, our results suggest that the core system used to process quantities does not involve the angular gyrus. The verbal-related regions that were active were not restricted to the right Rolandic operculum. We also found sporadic activations in pars orbitalis and pars opercularis, regions known to be involved in language processing (Saur et al. 2008). Such findings lend support to the view that verbal areas are automatically engaged when adults manipulate numbers. The exact role played by each of the 3 structures should be addressed in further research.

Interestingly, the contrast between the analogue and symbolic systems did not reveal differences in verbal-related areas. This result could suggest that the participants used subvocalization to compare not only symbolic but also analogue stimuli. This point might be of importance as it suggests that adults automatically rely on verbal cues to facilitate the decision even though the task might not necessarily require a verbal response. The finding that the analogue path mobilizes more brain areas, as evidenced by the analogue > symbolic contrast (see Fig. 5F), may reflect that extracting the magnitude from a physical stimulus is more resource demanding for the visual areas than retrieving the value from a symbolic stimulus.

Conversely, since symbolic processing implies verbal components, one could have expected that the symbolic > analogue contrast would highlight some verbal areas. However, as discussed in the previous paragraph, the comparison of analogue quantities does not preclude the activation of verbal knowledge. This view is supported by the conjunction analysis of analogue conditions (Fig. 4B), which shows that verbal knowledge is called upon to complete the task. That no statistically significant difference was detected does imply that activation levels were similar between the analogue and symbolic conditions but does not rule out the hypothesis that the verbal content was different. For example, whereas the comparison of positive integers activates symbols such as “3,” the approximate condition might have activated verbal quantifiers such as “larger” (disk). Further research should evaluate, separately for analogue and symbolic processing, to which extent verbal activation is attributable to number processing and to the task (i.e., comparing 2 items along a determined dimension).

**A Functional Framework for Number Mining**

We propose a theoretical attempt to systematize the knowledge about number mining and the pattern of activity concerned with
magnitude coding (see Fig. 6). In line with the approach suggested by Arsalidou and Taylor (2011), we recommend updating the triple-code model (Dehaene et al. 2003). Our use of cytoprobabilistic maps, together with the cHRF and its time derivative, enables us to propose a finer-grained map of the anatomical structures involved in quantity processing.

The flowchart in Figure 6 depicts the information flow underpinning the number sense. The system is composed of 3 functional sets: the spatial core of the system, the culturally recycled plug-ins, and the number mining modules. The spatial core regroups the anatomical structures that code magnitudes as spatial quantities. This system has been inherited from primates as indicated by the similar performance of animals (Nieder et al. 2002) and non-educated humans (Pica et al. 2004) in completing basic numerical tasks. The “inherited” system represents magnitudes in a logarithmic format until it receives proper training to improve its ability to represent quantities. In line with the distinction between approximate and exact spatial mapping of magnitudes, we distinguished 2 subparts: While neurons in hIP2 are encoding approximate quantities such as bar length or disk size, neurons in hIP3 respond to exact values (e.g., as the number of dots in an array).

The culturally recycled regions regroup the anatomical structures that were recruited to serve new, evolutionary-relevant functions (Dehaene and Cohen 2007). Since these regions add specific capabilities to the core system, we term them plug-ins. The verbal code plug-in refers to the area in charge of storing the visual representations of Arabic digits. The visual patterns of Arabic digits are associated to the neurons in hIP3 (which code exact quantities). Whenever an Arabic digit is recognized, the neurons coding for the given magnitude are activated. The verbal plug-in constitutes the last stage of a symbolic recognition process. As such, there is no quantity extraction made along the path, rather the quantity is associated to the symbol and automatically activated in case of recognition. Another plug-in enables the retrieval of simple facts to perform arithmetical operations (such as multiplication). This plug-in has been localized in the left angular gyrus (see Dehaene et al. 2003 for the theory and Grabner et al. 2009 for empirical evidence). The last plug-in we identified codes for the notion of negativity. The present study shows that negativity is coded in the left superior parietal lobule. This plug-in connects to the core system to integrate the notion of negativity into an independent representation of a magnitude.

Some components of the system are highly sensitive to format. For example, the left ventral V3 and the right V1 have been shown to modulate their levels of activity in both the dots > disk and negative > positive contrasts. In addition, the system depicted in Figure 6 could be expanded by adding a decision-supporting module in charge of holding information online (which would account for the frontal activations) and a motor module in charge of computing the behavioral responses (with a center of gravity in BA6).

The experiment presented in this article has deepened our understanding of numerical cognition. Similar to Santens et al. (2010), we reached the conclusion that number-sensitive neurons can be accessed by various pathways. For each format, we further specified the network supporting number mining. A limit in mapping the possible areas sensitive to format is that we could not test all the possible visual formats. Further research can complete our work by testing the comparison of various other formats (e.g., roman format). A second limit is that the role of the verbal regions remains unclear when the stimuli are in analogue format. This is another question that is to be addressed in further research.

Evidently, each tenet underlying the proposed mapping of the triple-code model (Dehaene et al. 2003) can be tested. Since a major conclusion of our research is the putative functional difference between the neurons in hIP2, coding approximate magnitudes, and the neurons in hIP3, coding exact quantities, it is crucial to replicate our results with

Figure 6. Proposed functional neuroanatomy for the extraction and comparison of quantities (mapped into the triple-code model; Dehaene et al. 2003).
equivalent material. For example, to yield a functional map of the hIPs that can be compared with our own, we suggest replicating our experiment with the use of other material to implement exact (e.g., roman numeral) and approximate quantities (e.g., bar length). Central to our model is the prediction that comparing roman numerals will activate hIP3 neurons, while comparing bars will yield a peak of activity in hIP2 neurons. Furthermore, contrasting the activation sites obtained during the comparison of bars with our activation map of the disk condition could reveal a difference in peak site in hIP2 region. Such a difference would show that the coding of approximate quantities is dependent on format and thus would suggest that number mining influences how quantities are ultimately coded in the hIPs. In addition, it would be of great interest to manipulate the visual features of targets and their spatial distribution in the display so as to disentangle number mining processes from attentional processes. The proposed approach will not only test whether the areas we identified as number mining are active when processing other types of material but it also might enable the identification of other number mining areas. Finally, using the material we used in various numerical tasks will challenge the robustness of our mapping by possibly revealing that some areas are task dependent rather than format sensitive. As understanding negativity is a crucial step in the development of mathematical abilities, would it be for its role in physics, it seems essential to conduct further research in this direction. The model posits that hIP3 neurons are the actual recipients coding exact quantities and that left SPL neurons code for negativity. In line with our model, an experiment requiring the participants to learn an association of new symbols with integers would lead to 2 predictable results. First, neurons in hIP3 should not be active during the passive viewing of the symbols before learning has taken place, but these neurons should be active afterward. Second, an association of symbols with negative integers will activate not only hIP3 neurons but also left SPL neurons. Should not both results be found, then the proposed model would require revision.

What our key findings and theoretical framework highlight is a crucial distinction between the processing of symbolic stimuli and the processing of analogue stimuli. For analogue stimuli, number mining requires much visual processing within early visual areas, the neural signal being ultimately processed in the parietal cortex. The neurons that eventually code the magnitude are lateralized to the right. If the quantity is approximate, then only hIP2 neurons respond. If the quantity is exact, then hIP2 and hIP3 neurons respond. Number mining with respect to symbolic stimuli is a process of an altogether different nature. The signal is processed along the ventral pathway until recognition of the Arabic digit is completed. Thereafter, the activation spreads to the associated neurons in hIP3. Supplementary plug-ins, such as negativity or fact retrieval, can enter the game whenever required. We conclude that, in a restricted sense, the concept of number mining applies to analogue but not symbolic stimuli, the processing of which is closer to pattern recognition.

Supplementary Material
Supplementary material can be found at: http://www.cercor.oxfordjournals.org/

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