The Magnitude Representation of Small and Large Symbolic Numbers in the Left and Right Hemisphere: An Event-related fMRI Study

Karolien Notebaert, Sabine Nelis, and Bert Reynvoet

Abstract

Numbers are known to be processed along the left and right intraparietal sulcus. The present study investigated hemispheric differences between the magnitude representation of small and large symbolic numbers. To this purpose, an fMRI adaptation paradigm was used, where the continuous presentation of a habituation number was interrupted by an occasional deviant number. The results presented a distance-dependent increase of activation: larger ratios of habituation and deviant number caused a larger recovery of activation. Similar activation patterns were observed for small and large symbolic numbers, which is in line with the idea of a more coarse magnitude representation for large numbers. Interestingly, this pattern of activation was only observed in the left parietal cortex, supporting the recently proposed idea of Ansari [Ansari, D. Does the parietal cortex distinguish between “10”, “Ten,” and Ten Dots? Neuron, 53, 165–167, 2007] that the left parietal cortex is specialized in the processing of encultured symbolically presented numbers.

INTRODUCTION

In the last decade, brain imaging studies have provided evidence for a bilateral activation of the intraparietal sulcus (IPS) whenever participants are engaged in numerical tasks relying on mental number line access. These tasks include comparing Arabic digits (Fias, Lammertyn, Reynvoet, Dupont, & Orban, 2003; Pinel, Dehaene, Rivière, & Le Bihan, 2001; Pesenti, Thioux, Seron, & De Volder, 2000; Chochon, Cohen, van de Moortele, & Dehaene, 1999), producing or verifying the results of simple calculations (Simon, Mangin, Cohen, Bihan, & Dehaene, 2002; Zago et al., 2001; Pesenti et al., 2000), and identifying a predefined target in a continuous stream of numbers (Eger, Sterzer, Russ, Giraud, & Kleinschmidt, 2003). These IPS activations are observed with numbers presented as symbolic stimuli (i.e., as Arabic or verbal numerals; Eger et al., 2003), nonsymbolic discrete stimuli (such as dot patterns; Dormal & Pesenti, 2009; Piazza, Pinel, Le Bihan, & Dehaene, 2007; Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004), or continuous stimuli (such as length of lines or amplitudes of angles; Dormal & Pesenti, 2009; Fias et al., 2003).

However, little is known about potential differences between the magnitude representation of small and large symbolic numbers, which forms the first focus of this study. The frequently observed size effect (e.g., Dehaene, 1992) reflects the observation that, for the same numerical distance, two small numbers (e.g., “2” and “3”) are easier to discriminate compared with two large numbers (e.g., “8” and “9”). This effect suggests that large numbers are less exactly represented compared with small numbers.

The idea that large numbers are more vaguely represented can be explained by different principles. A first principle is magnitude coding (e.g., Zorzi & Butterworth, 1999), which implies an analogy between the mental code of a number and the actual magnitude it represents. In other words, larger numbers will activate not only their own neuronal sets but also the neuronal sets of all smaller numbers, leading to a fuzzier representation for larger numbers. Alternatively, larger numbers can be more vaguely represented due to a decreasing distance between their magnitude representations on the number line (i.e., compressed scaling; Dehaene, 1992) and/or wider tuning curves (i.e., increasing variability; Gallistel & Gelman, 1992), both leading to a larger overlap of neighboring magnitude representations when the size of numbers increases. The idea of compressed scaling for nonsymbolic magnitudes has been supported by a study of Piazza et al. (2004). In the behavioral part of this study, participants had to indicate in a series of four dot clusters whether the last dot cluster contained a deviant number of dots. Dot clusters ranged between 8 and 32. When responses were plotted on a linear scale, performance curves for small and large numerosities were asymmetrical and broader for larger numerosities. When plotted on a log scale, the curves became symmetric and Gaussian with an identical width for both numerosities. This is in agreement with Weber’s law, assuming that a larger
Numerical distance between larger numerosities is needed to maintain a constant level of discrimination performance. These results led the authors to suggest that numbers are distributed on a logarithmic or compressed scale, resulting in an increasingly coarser magnitude representation for larger numbers.

Although the meta-analysis of Dehaene, Piazza, Pinel, and Cohen (2003) suggests that both hemispheres have number processing capacities, the question of whether they are characterized with a different magnitude representation remains to be answered. This forms the second focus of the present study. Recently, some studies have suggested that the left hemisphere (LH) contains a more exact magnitude representation compared with the right hemisphere (RH). Evidence firstly comes from a fMRI adaptation study of Piazza et al. (2004), using nonsymbolic stimuli. After passively viewing dot clusters with a fixed numerosity, participants were presented a dot cluster with a deviant numerosity. The presentation of a deviant numerosity led to a bilateral recovery of the BOLD signal in the IPS. Parametric analyses showed that the increase of activation was directly related to the numerical distance between the adapted dot cluster and the deviant dot cluster. Interestingly, the left IPS appeared to be more precise in differentiating between numerosities, as reflected in a smaller Weber fraction \( w = 0.18 \) compared with the RH \( w = 0.25 \). This would imply that there is less partial overlap between magnitude representations of nearby magnitudes in the LH, whereas the RH contains larger overlapping magnitude representations from nearby magnitudes. Additional evidence for the idea of a more exact magnitude representation comes from TMS studies. A TMS study of Andres, Seron, and Olivier (2005) showed that stimulation of the left posterior parietal cortex appeared to be sufficient to disturb exact digit discrimination, whereas approximate numerical judgments were only disturbed after applying TMS on bilateral posterior parietal regions. This finding was replicated in a more recent TMS study of Cappelletti, Barth, Fregni, Spelke, and Pascual-Leone (2007) who found that comparing double-digit numbers was more disturbed after applying TMS on the left IPS. Moreover, this effect was modulated by numerical distance, with a larger impairment of comparing close numbers. Finally, recent support comes from a visual half-field study by Notebaert and Reynvoet (2009). As a result of the neuroanatomical organization of our visual system, stimuli that are presented to our left visual field will be processed in our RH and stimuli presented in our right visual field will be processed in our LH. To investigate the magnitude processing capacities of both hemispheres, the priming distance effect was investigated in both hemispheres. The priming distance effect refers to the observation that targets preceded by numerically close primes (e.g., “1” preceded by “2”) elicit faster responses than targets preceded by numerically far primes (e.g., “1” preceded by “4”). Using two-digit numbers revealed a significantly steeper priming curve when targets were presented in the left visual field compared with targets presented in the right visual field. These results suggest a less precise magnitude representation in the RH, possibly due to a larger overlap of magnitude representations.

The present study investigated the magnitude representation of small and large symbolic numbers in the LH and RH. To this purpose, a fMRI adaptation study with small and large numbers was used. In this paradigm, a given stimulus is repeatedly presented, which causes the BOLD signal to decrease due to a reduction of firing rates of a neuronal population (Grill-Spector & Malach, 2001). Afterward, a stimulus attribute is changed, which may lead to recovery of the BOLD signal, indicating that the adapted neuronal population contains neurons that are sensitive to the changed attribute. If the signal remains adapted, the neuronal population is invariant to this attribute. Because the study of Piazza et al. (2007) has illustrated that adaptation to magnitudes in the parietal cortex is a slow, continuous process, the present study opted for a long habituation period. Small numbers in the present study comprised all numbers up to 12. Because these are the only numbers in Dutch whose corresponding number words do not have a transparent 10-unit structure, they are believed to have a special status in our numerical system (Nuerk, Weger, & Willmes, 2001). Furthermore, as stated in the neural model by Verguts, Fias, and Stevens (2005), numbers up to 15 are the most frequently used subset of numbers, and it is therefore suggested that these numbers are represented more exactly. Both reasons resulted in the selection of numbers up to 12 as the small numbers and double digits above 15 as the large numbers. The use of small and large symbolic numbers in combination with long habituation periods allowed to directly compare magnitude adaptation and recovery effects for both symbolic magnitudes in both hemispheres. Up to date, this has never been done before and should shed light on potential hemispheric differences between the representation of small and large symbolic numbers.

**METHODS**

**Participants**

Thirteen healthy participants (7 men and 6 women, age range = 21–30 years) took part in the study in return for payment. All participants were right-handed, had no history of neurological or psychiatric disorders, and had a normal or corrected-to-normal vision. They were all native Dutch speaking and were unaware of the purpose of the study. Written informed consent was obtained from all participants. The study was approved by the K.U. Leuven Medical Ethics Committee (ML3431).

**Stimuli**

The continuous presentation of a number (i.e., the habituation number) was interrupted by an occasional deviant
number. The habituation numbers (6 and 32) and deviant numbers (3, 4, 5, 8, 9, 12 for the small numbers; 16, 20, 26, 40, 48, 64 for the large numbers) were all presented as Arabic numerals in black on a gray background. To avoid low-level perceptual repetition effect, the numbers were presented in two different fonts (Times New Roman, font size 16 pt, and Courier New, font size 16 pt) and on six different locations of the screen, each defined at 2° from the center of the screen. The font of the stimuli was fully randomized, whereas the location of the stimuli was pseudorandomized, with the restriction that one location was never used two times in a row.

**Design and Procedure**

At the start of the experiment, a short localizer scan was acquired for each individual to identify those regions involved in mental calculation. This localizer scan consisted of two tasks, a subtraction task and a sentence reading task. During the subtraction task, participants were asked to mentally calculate the outcome of subtractions, presented in full sentences (e.g., “Subtract seven from ten”). During the sentence reading task, random Dutch sentences were presented, which had to be silently read (e.g., “The cat sits in the tree”). Both tasks consisted of two blocks of 20 sentences each, presented to the participants in either the ABBA or the BAAB order, with A being a block of the subtraction task and B a block of the sentence reading task. All subtractions and sentences were presented in Courier New (font size 16 pt) and remained on the screen for 1500 msec, separated by a blank screen of 2000 msec. This localizer scan allowed us to define regions along the IPS for each individual, independently of the main experiment.

In the main experiment, participants were asked to conduct a color detection task on two experiments, one with small and one with large numbers. Each experiment consisted of two series of numbers (i.e., runs). The order of the experiments was counterbalanced over participants. The procedure of the experiment with small numbers was identical to the one of the experiment with large numbers. In a continuous stream of numbers, participants were asked to press a button as quickly as possible whenever a red number was presented. All numbers remained on the screen for 200 msec, separated by a blank screen of 1200 msec (see Figure 1). The habituation number was always 6 in the experiment with small numbers and 32 in the experiment with large numbers. To avoid expectancy-based strategies from participants, the length of a habituation period before a deviant number was varied (i.e., between 5 and 9 presentations), with the average length of the habituation period being equal before each type of deviant number (i.e., 7 presentations). The numerical distance between the habituation and the deviant number was manipulated in such a way that the deviant number belonged to one of the following conditions. All conditions were defined as the ratio of the habituation and deviant number for the small and large numbers, respectively: (i) Ratio 1.25 (5/8 and 26/40), (ii) Ratio 1.5 (4/9 and 20/48), and (iii) Ratio 2 (3/12 and 16/64) (see Table 1). All deviant numbers were presented six times each within a run. A fourth ratio was added as a baseline condition, namely Ratio 1, which was a repetition of the habituation number. The baseline condition was presented 24 times in a run, with half of these trials containing a red-colored habituation number to which participants were asked to respond. Because previous research has shown that number processing and response selection activate the same regions in the parietal cortex (Göbel, Johansen-Berg, Behrens, & Rushworth, 2004), the response trials were excluded from the subsequent analyses. Each run was presented twice to the participants, which finally led to 24 observations for each ratio.

Stimulus presentation was synchronized with the fMRI sequence at the beginning of each run. A natural jitter was induced by creating an event length (1400 msec) that was not a multiple of the repetition time (2000 msec). The order of the conditions was counterbalanced for each run, in such a way that each condition followed every other condition equally often. In addition, we also systematically rotated the positions of the conditions across all runs, assuring that the average trial history

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<td></td>
<td>Habituation Number</td>
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<td>Small numbers</td>
<td>3</td>
<td>4</td>
<td>5</td>
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<td>Large numbers</td>
<td>16</td>
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preceding and following a given condition was the same as for any other condition.

**fMRI Data Acquisition and Processing**

The fMRI images were acquired with a 3-T Intera MR scanner (Philips, Best, Netherlands) using an eight-element SENSE head coil (MRI Devices Corp., Waukesha, WI). A functional time series consisted of whole-brain BOLD-weighted field-echo planar images with repetition time/echo time = 2000/30 msec, in-plane resolution = 2.75 × 2.75 mm², acquisition matrix = 80 × 80, SENSE reduction factor = 2, and slice thickness = 3.75 mm, acquiring 36 horizontal slices covering the entire brain. At the end of each scanning session, a three-dimensional, high-resolution, T1-weighted anatomical image (repetition time/echo time = 9.68/4.6 msec, TI = 1100 msec, field of view = 250 mm², matrix = 256 × 256, slice thickness = 1.2 mm, 182 slices, SENSE factor = 2) was acquired.

Data were processed and analyzed with SPM5 (http://www.fil.ion.ucl.ac.uk/spm) implemented in MATLAB (MathWorks, Natick, MA). The first four images were discarded to allow for T1 equilibration. The remaining images were realigned to the first image and corrected for slice timing. T1-weighted anatomical images were then coregistered to the first scan of the functional images. In a next step, the anatomical image was segmented and normalized to the standard template of the Montreal Neurological Institute by means of an affine fourth degree β-spline interpolation transformation and resampled to a 2 × 2 × 2 mm³ voxel size. The resulting spatial normalization file was subsequently used to normalize and rewrite the functional images. Finally, functional images were spatially smoothed (FWHM 8 mm).

**Data Analysis**

The imaging data were analyzed using two different approaches. Firstly, the localizer task was used to define for each individual the anatomical locus of mental calculation. To this purpose, the average activation of the calculation task was diminished with the average activation of the sentence reading task. This resulted for each individual the anatomical locus of mental calculation. To this purpose, the average activation of the calculated area was used to normalize and rewrite the functional images. Finally, pairwise comparisons (one-sample t tests). In a next step, hemispheric differences were further analyzed by performing a 2 × 2 × 7 ANOVA with hemisphere (left vs. right), magnitude of the numbers (small vs. large numbers), and ratio (Ratio 2 < HAB, 1.5 < HAB, 1.25 < HAB, 1, 1.25 > HAB, 1.5 > HAB, 2 > HAB) as within-subject factors. Given the absence of a right parietal region for Subject 9, the subject was discarded from this analysis.

For the second approach, a whole-brain group analysis was conducted searching for brain regions presenting a significant linear increase of activation for larger ratios (p < .001, corrected on cluster level). The linear increase of activation was modeled by weighting each ratio differently. More specifically, the weights −3, −1, 1, and 3 were given for the habituation number, Ratio 1.25, Ratio 1.5, and Ratio 2, respectively. Within the resulting brain region, the average activation level (betas) for each ratio was extracted for each individual using MarsBar. The resulting betas were submitted to a 2 × 7 ANOVA with magnitude of the numbers (small vs. large numbers) and ratio of habituation and deviant number (Ratio 2 < HAB, 1.5 < HAB, 1.25 < HAB, 1, 1.25 > HAB, 1.5 > HAB, 2 > HAB) as the within-subject factors, followed by pairwise comparisons (one-sample t tests).

**RESULTS**

Using the first approach, the localizer task resulted for each individual in a significantly activated region along the left IPS and for 12 of 13 participants in a cluster along the right IPS (Table 2). In the left parietal voxels, a distance-dependent increase of activation was found, resulting in a significant effect of Ratio, F(6, 70) = 3.376, p = .005. For deviants smaller than the habituation number, significantly more activation was found for all deviants compared with the habituation number: 1.25 versus 1, t(25) = −2.35, p < .05; 1.5 versus 1, t(25) = −2.4, p < .05; and 2 versus 1, t(25) = −2.58, p < .01. The differences between the deviants were nonsignificant: 1.5 versus 1.25, t(25) = 0.39, p = .35; 2 versus 1.5, t(25) = 0.16, p = .44; and 2 versus 1.5, t(25) = −0.3, p = .62. For the deviants larger than the habituation number, significantly more activation was observed for the Ratio 1.5, t(25) = −1.72, p < .05, and Ratio 2, t(25) = −5.65, p < .001, both compared with the habituation number. Furthermore, significantly more activation was observed for Ratio 2 compared with Ratio 1.25, t(25) = −2.48, p < .05, and marginally significantly more activation was observed for the Ratio 1.5 compared with Ratio 1.25, t(25) = −1.56, p = .065. All other pairwise comparisons revealed nonsignificant differences: 1.25 versus HAB, t(25) = 0.64, p = .74; and 2 versus 1.5, t(25) = −0.39, p = .35. The effect of magnitude of the numbers and the interaction effect between both variables were nonsignificant (both F < 1). In the right parietal voxels, there was no significant effect of ratio or magnitude of the numbers (both F < 1). Also the interaction effect between both variables appeared to be nonsignificant, F(6, 70) = 1.33, p = .256. The results are presented in Figure 2. Furthermore, the 2 × 2 × 7
A N O V A resulted in a significant effect of Hemisphere, $F(1, 11) = 5.87, p < .05$, with on average more activation in the LH. In addition, a significant interaction effect was observed between Hemisphere $\times$ Ratio, $F(6, 66) = 2.3, p < .05$. All other effects were nonsignificant: Ratio, $F(6, 66) = 1.55, p = .18$; Magnitude $\times$ Ratio, $F(6, 66) = 1.04, p = .41$; all other effects $F < 1$.

The second approach revealed a linear increase of activation for larger ratios in a region along the left IPS ($-42 -50 46, k = 70, p < .0001$, corrected at cluster level, see Figure 3). This contrast failed to reveal an analogue region in the RH. Within the selected ROI, a marginally significant effect of ratio was observed, $F(6, 70) = 2.30, p = .072$. For the deviants smaller than the habituation number, significantly more activation was observed for Ratio 2, $t(25) = -2.61, p < .01$, and marginally significantly more activation for Ratio 1.5, $t(25) = -1.55, p = .07$, both compared with the habituation number. Furthermore, marginally significantly more activation was observed for Ratio 2 compared with Ratio 1.25, $t(25) = -2.03, p < .01$, and compared with Ratio 1.5, $t(25) = -1.90, p < .05$.

All other pairwise comparison revealed nonsignificant differences: 1.25 versus HAB, $t(25) = 0.35, p = .73$; 1.5 versus HAB, $t(25) = 0.75, p = .45$; 2 versus 1.5, $t(25) = -0.47, p = .64$; and 1.5 versus 1.25, $t(25) = -1.04, p = .32$. The effect of magnitude of the numbers and the interaction effect between both variables were both nonsignificant (both $F < 1$). The results are also presented in Figure 3.

DISCUSSION

This event-related fMRI study aimed at clarifying potential hemispheric differences between the magnitude

The localizer scan consisted of a sentence reading task and a subtraction task. Average activation of subtraction task was diminished with average activation for sentence reading task in order to find the neural locus of mental calculation for each individual.

Figure 2. Activation levels for all ratios of habituation and deviant number in the left and right parietal voxels resulting from the localizer scan.
representation of small and large symbolic magnitudes. Using an adaptation paradigm, the continuous presentation of small and large numbers was interrupted by an occasional deviant number, allowing us to investigate recovery effects along the left and right IPS. Two different approaches were used, both leading to similar results. The localizer scan resulted for each individual in significant activation along the left IPS and for 12 participants in significant activation along the right IPS. This is in line with a recent study of Pinel et al. (2007), in which the same localizer scan led to similar activation patterns. Within the left IPS voxels, a distance-dependent increase of activation was observed: larger ratios of the habituation and deviant number caused larger recovery of activation. Interestingly, this effect was absent in the right parietal voxels. The same results were found for small and large numbers, as reflected in the absence of an interaction effect between the magnitude of the numbers and the ratio of the habituation and deviant number. The hemispheric differences were statistically confirmed in a subsequent analysis, showing a significant interaction effect between hemisphere and ratio. Due to the absence of a distance-dependent recovery of activation in the right parietal voxels, the general effect of ratio across hemispheres appeared nonsignificant. The second approach resulted in similar results. Conducting a whole-brain group analysis searching for brain areas presenting a linear increase of activation for increasing ratios revealed a significantly activated cluster along the left IPS. An analogue cluster of activation appeared absent in the RH. Again, the same activation pattern was found for small and large numbers.

The first aim of this study was to shed light on differences between the magnitude representation of small and large symbolic numbers. A similar pattern of recovery of activation was found for both small and large magnitudes, resulting in a nonsignificant interaction effect between magnitude of the numbers and ratio of the habituation and deviant number. This suggests that large numbers are
more coarsely represented than small numbers. To observe an equally large recovery of activation, the same ratio—and thus a larger absolute numerical distance between the habituation and deviant number—is necessary for large numbers compared with small numbers. This is in agreement with the general idea that large numbers are more coarsely tuned than small numbers (e.g., Dehaene, 1992), caused by either compressed scaling (Dehaene, 1992) or increasing variability (Gallistel & Gelman, 1992). The recovery effects in the LH present a typical V-curve, which is not in agreement with the magnitude coding principle (e.g., Zorzi & Butterworth, 1999). According to magnitude coding, deviants smaller than the habituation number would not lead to a distance-dependent recovery of activation but to an equally large adaptation to these deviants because all numbers also activate the neuronal sets of all smaller numbers. This is not in line with the present results: Both deviants smaller and larger than the habituation number caused a distance-dependent recovery of activation. Moreover, the observation of a typical V-curve for both small and large numbers is in line with the idea that symbolic numbers are represented by a place coding system (for a recent overview, see Verguts & Fias, 2008). According to this principle, numbers activate their own corresponding set of neurons and will partially activate the neuronal set of neighboring magnitudes with a decreasing strength as a function of numerical distance. Place coding implies an equally large priming effect from primes smaller than the target compared with primes larger than the target. This has been supported by many priming studies using small symbolic magnitudes (e.g., Reynvoet, Brysbaert, & Fias, 2002; Reynvoet, Caessens, & Brysbaert, 2002), showing a priming curve symmetric around the target number. Interestingly, this pattern of results occurred for both small and large numbers in the present study, assuming that the place coding mechanism is at work not only for small symbolic numbers but also for large symbolic numbers. These recovery patterns are in line with the results of the adaptation study of Piazza et al. (2004), in which nonsymbolic numbers were used. Also in this study, the pattern of recovery of parietal activation presented a V-shape curve, suggesting place coding of nonsymbolic and symbolic numbers.

The second aim of the present study was to reveal hemispheric differences in the representation of small and large numbers. Although the localizer task resulted in activation of left and right regions along the IPS, only the left IPS activation exhibited a distance-dependent increase of activation. Larger ratios of the deviant and habituation numbers resulted in a larger recovery of activation. This finding was replicated using the second approach that revealed a linear increase of activation in the left IPS, whereas no similar pattern of activation was found in the RH. These results are not in line with the results of Piazza et al. (2004), where nonsymbolic magnitudes were used. A distance-dependent recovery was observed in the left and right IPS. The results of both studies support the recently proposed idea of Ansari (2007) that the LH is specialized in encultured magnitude representations, possibly resulting from connections with left-frontal regions involved in language processes. This argument was based on results of a recent fMRI study. For instance, in a fMRI study of Piazza et al. (2007), participants were presented with nonsymbolic (i.e., dot clusters) or symbolic stimuli (i.e., Arabic numerals). After continuous presentation of numbers within a small range, distance-dependent recovery of the activation in the IPS and frontal regions was observed when a deviant number was shown, irrespective of format changes between the adapted and the deviant numbers. However, in the left IPS, this effect was smaller when Arabic digits were followed by deviant dots compared with the condition where dots were followed by deviant Arabic digits. The authors interpreted this observation as an indication for a more refined magnitude coding of symbolic numbers in the LH. The RH on the other hand would be characterized with a rather coarse magnitude representation for both symbolic and nonsymbolic numbers. Taken into account these results, Ansari suggests that the left IPS contains a precise representation of encultured symbols of magnitude.

The findings of the present study seem to be—at first sight—contradictory to the findings of a more recent study of Notebaert, Pesenti, and Reynvoet (2010). In this study, participants were asked to conduct a number identification task on prime-target pairs, both presented as small symbolic numbers (i.e., Arabic digit and word numbers). The authors observed a distance-dependent recovery of activation positively correlated with the distance between primes and targets: The larger the prime-target distance, the higher the recovery of activation. The same pattern of results was observed in both hemispheres, suggesting no hemispheric differences in magnitude representation. Moreover, the results of Notebaert et al. (2010) are in line with the findings of Naccache and Dehaene (2001). When participants had to compare a target that was preceded by a prime, either in the same or in a different notation (i.e., Arabic digits and word numbers), decreased activation was found in the IPS bilaterally. To account for the different results of both studies, we will extend Ansari’s proposed hypothesis of a left hemispheric specialization in processing symbolic numbers. We propose the intention to process numbers to be a crucial factor in explaining the differences between these studies. In the two latter studies, participants were asked to intentionally process the magnitude of these numbers due to the task at hand. In the studies of Notebaert et al. and Naccache and Dehaene, a target identification task and a comparison task were used respectively, whereas in the present study a passive viewing task was used. We argue that when participants are submitted to a task that does not require intentional processing of symbolic numbers, only the LH, specialized in processing symbolic numbers, will automatically process the magnitude information. The RH on the other hand would require intentionally processing of the magnitude information to exhibit magnitude adaptation and thus recovery effects.
The proposed hypothesis also seems to be in contrast with the results of a recent fMRI adaptation study of Cohen Kadosh, Cohen Kadosh, Kaas, Henik, and Goebel (2007). Using a passive viewing task, two sequential symbolic numbers were presented in either the same notation (Arabic digits or word numbers) or in a mixed notation. When numbers were presented in the same notation, adaptation was observed in the left and right parietal cortex. However, for mixed notation trials, adaptation was only observed in the left parietal cortex, leading the authors to suggest that only the left parietal cortex contains a notation-independent magnitude representation. The observation of adaptation in the right parietal cortex for identical notation trials seems to be in contrast with our proposed hypothesis. However, this study only used trials containing two identical or two different numbers and is lacking the manipulation of numerical distance between the two numbers. This implies that the adaptation effects for these trials might be resulting from visual priming rather than magnitude priming, which is supported by previous studies showing repetition suppression in the parietal cortex after repeated presentation of stimuli (for a recent overview, see Grill-Spector, 2008). Cross-notation adaptation on the other hand cannot be explained by visual priming, and under these conditions no adaptation was observed in the right parietal cortex, which is in line with our hypothesis. We argue that the absence of a cross-notation adaptation effect in the right parietal cortex does not reflect a notation-dependent magnitude representation but is caused by the absence of an intentional processing of the numbers in the passive viewing task. Note that a similar hypothesis in terms of intentional versus automatic processing has been brought forward to explain differences between studies supporting either notation-independent or notation-dependent magnitude processing (Cohen Kadosh & Walsh, 2009, but see Reynvoet & Notebaert, 2009).

To account for the results observed in the RH, two different explanations can be brought forward. Firstly, the pattern of results in the right parietal voxels could indicate a very fuzzy magnitude representation of symbolic numbers, leading to an equally large adaptation following the habituation number and all deviants. Secondly, this observation could reflect the absence of global adaptation to symbolic magnitudes in the right parietal voxels. The best way to directly test both suggested explanations is to make a comparison with a condition where no adaptation period preceded a deviant number. Because we are lacking such baseline condition to test the presence or absence of a global adaptation effect in the right parietal voxels, we focus on previous research, which we believe is in support for the second explanation. Theoretically, it is more likely to assume the absence of an adaptation effect for all ratios rather than to assume the presence of an equally large priming or adaptation effect in all conditions. According to the model of Verguts et al. (2005), the overlapping magnitude representations lead to a strong activation of neighboring magnitudes and less activation of magnitudes numerically further away, resulting in the typical priming distance effect as observed in many previous behavioral studies (e.g., Reynvoet, Brysbaert, et al., 2002; Reynvoet, Caessens, et al., 2002; Koechlin, Naccache, Block, & Dehaene, 1999). Previous behavioral studies have shown that when the numerical distance between prime and target became larger than 3 or 4, there was hardly any effect of the prime on the target (e.g., Roggeman, Verguts, & Fias, 2007). In our study, where the numerical distance between the habituation number and the deviant number varies between −3 and 6 for the largest ratios in the experiment with small numbers, we believe that there was little or no adaptation for these ratios. Therefore, Ratio 2 can serve as a baseline to examine adaptation effects in the other conditions. Because there were no significant differences between this ratio and all other ratios in the right parietal voxels, we argue for the absence of a global adaptation effect.

To conclude, the present study investigated possible hemispheric differences between the magnitude representation of small and large symbolic numbers. The results clearly show a distance-dependent increase of parietal activation for small and large numbers: Larger ratios of habituation and deviant numbers led to larger recovery of parietal activation. This suggests that large numbers are more coarsely tuned compared with small numbers, in line with Weber’s law. Interestingly, this pattern of results was only observed in the left parietal cortex, which is in agreement with the idea that the left parietal cortex is specialized in the processing of encultured symbolically presented numbers.

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