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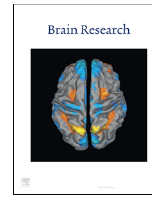

Research Report

Non-symbolic and symbolic notations in simple arithmetic differentially involve intraparietal sulcus and angular gyrus activity

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ABSTRACT

Addition problems can be solved by mentally manipulating quantities for which the bilateral intraparietal sulcus (IPS) is likely recruited, or by retrieving the answer directly from fact memory in which the left angular gyrus (AG) and perisylvian areas may play a role. Mental addition is usually studied with problems presented in the Arabic notation (4+2), and less so with number words (four+two) or dots (:: +·.). In the present study, we investigated how the notation of numbers influences processing during simple mental arithmetic. Twenty-five highly educated participants performed simple arithmetic while their brain activity was recorded with functional magnetic resonance imaging. To reveal the effect of number notation, arithmetic problems were presented in a non-symbolic (*Dots*) or symbolic (*Arabic*; *Words*) notation. Furthermore, we asked whether IPS processing during mental arithmetic is magnitude specific or of a more general, visuospatial nature. To this end, we included perception and manipulation of non-magnitude formats (*Colors*; unfamiliar Japanese *Characters*). Increased IPS activity was observed, suggesting magnitude calculations during addition of *non-symbolic* numbers. In contrast, there was greater activity in the AG and perisylvian areas for *symbolic* compared to non-symbolic addition, suggesting increased verbal fact retrieval. Furthermore, IPS activity was not specific to processing of numerical magnitude but also present for non-magnitude stimuli that required mental visuospatial processing (*Color*-mixing; *Character*-memory measured by a delayed match-to-sample task). Together, our data suggest that simple non-symbolic sums are calculated using visual imagery, whereas answers for simple symbolic sums are retrieved from verbal memory.

1. Introduction

The ability to perform mental arithmetic is a prerequisite for more advanced mathematical skills. Arithmetic proficiency progresses from solving non-symbolic sums (e.g., adding two pieces of fruit) to manipulation of symbols that represent quantities (e.g., “1+1”, or “one+one”). With sufficient practice both non-symbolic and symbolic problems can be solved mentally, without needing fingers or pen and paper for visualizing numerosity. Evidence supports that two main processing routes are available for mental arithmetic: answers can be calculated by making use of a fronto-parietal network that includes the magnitude system in bilateral intraparietal sulcus (IPS) and/or answers can be directly retrieved from verbal fact memory with the angular gyrus (AG) as a key brain structure (Dehaene et al., 2003). Behavioral research indicates that the manner in which sums are solved depends on the notation of the numbers within the arithmetic problem. For

Abbreviations: IPS, intraparietal sulcus; AG, angular gyrus; RT, reaction time; fMRI, functional magnetic resonance imaging; ANOVA, analysis of variance; MFG, middle frontal gyrus; IFG, inferior frontal gyrus; ITG, inferior temporal gyrus; Hem., Hemisphere; L, left; R, right; hIP1, human intraparietal area 1; hIP2, human intraparietal area 2; hIP3, human intraparietal area 3; FWE, family wise error corrected; pMTG, posterior middle temporal gyrus; MTG, middle temporal gyrus; HC, hippocampus; pCC, posterior cingulate cortex; aCC, anterior cingulate cortex; medSFG, medial aspect of the superior frontal gyrus; SFG, superior frontal gyrus; TP, temporal pole; ISI, inter-stimulus interval; EPI, echo-planar imaging; TR, repetition time; TE, echo time; FA, flip angle; FOV, field of view; MNI, Montreal Neurological Institute; GLM, general linear model; BOLD, blood-oxygenation-level dependent; HRF, hemodynamic response function; ROI, region of interest

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example, university students report to use retrieval more often for simple problems notated in Arabic numbers than for simple problems notated in number words (Campbell and Alberts, 2009). The first aim of the current study was to find neural evidence to support this behavioral finding by assessing whether brain processing used for solving simple addition problems differs according to the format in which the numbers are notated (*non-symbolic*: dots (∷); *symbolic*: Arabic (4), words (four)). Because the IPS has been implicated in operations besides magnitude processing, such as general visuospatial processing (for reviews, see Grefkes and Fink, 2005; Kravitz et al., 2011), the second aim was to explore the nature of observed IPS activity, by investigating the degree to which processing in the IPS is specific to numerical magnitudes.

1.1. Behavioral research on arithmetic and notation

Behaviorally, there is abundant evidence that both calculation and retrieval can be used for solving arithmetical problems (Campbell and Alberts, 2009; Campbell and Fugelsang, 2001; LeFevre et al., 1996). Initially, a calculation strategy - also referred to as a procedural strategy - is employed. Calculation can be thought of as the manipulation of numerical magnitudes, or numerosities. However, with practice, sums and answers can be associated or stored together in memory as facts, such that the use of fact retrieval to solve the sums is employed more often (Shrager and Siegler, 1998). Therefore, the solution method for addition problems can vary depending on familiarity. Simple additions, for example, may especially rely on direct memory retrieval in adults, because these problem-answer combinations have been practiced many times (Ashcraft and Christy, 1995).

Concerning number notation, some have proposed that numerical processing is relatively abstract in nature (Dehaene et al., 2004; McCloskey and Macaruso, 1995), whereas others emphasize the influence of number notation (Campbell and Alberts, 2009; Campbell and Fugelsang, 2001; Campbell et al., 2004). The former idea stems from several number processing phenomena that are not influenced by number notation. One such phenomenon is the *distance effect* which refers to the finding that if one has to judge which of two numerical magnitudes is larger, discrimination is faster if the numbers are farther apart (i.e., participants are faster at discriminating 2 from 9 than 2 from 5). The fact that the distance effect is observed for both non-symbolic (dots: Buckley and Gillman, 1974) and symbolic number notations (Arabic: Moyer and Landauer, 1967; words: Foltz et al., 1984, exp 2) suggests that the cognitive system represents magnitude in an abstract format. On the other hand, Campbell and Fugelsang (2001) observed longer reaction times (RTs) for additions in word notation than for additions in Arabic notation, especially for the larger sums. Moreover, this notation by size effect was replicated in self reported strategy use, with more calculation for number words than for Arabic numbers, especially for the larger sums (cf. Campbell and Alberts, 2009; Campbell et al., 2004). These latter findings emphasize a possible difference in solution method according to the number notation of the problem, even if both notations are symbolic in nature.

In short, behavioral evidence shows that practice in solving arithmetic problems promotes direct retrieval of the answers from fact memory and that, even if the mental representation of magnitude is abstract, notation can have an influence on arithmetic performance. Although metacognitive self-reports provide valuable data, participants are not always aware of which solution methods they use and they may have difficulties in verbalizing them. Furthermore, self-reports are influenced by instruction (Kirk and Ashcraft, 2001; Smith-Chant and LeFevre, 2003), and even though they may be veridical reflections of mental processes, the arithmetic performance itself can be changed by the requirement to self-report (Smith-Chant and LeFevre, 2003). In this regard, the brain activation pattern may provide an objective insight into mental arithmetic and could help to tease apart underlying cognitive processes being discussed in behavioral literature.

1.2. Brain research on arithmetic and notation

1.2.1. IPS for calculation, AG/perisylvian areas for retrieval

Neurally, magnitude calculation and verbal retrieval show specific correlates. Dehaene and colleagues (Dehaene et al., 2003) proposed that the horizontal segment of bilateral IPS is important for calculation, because it is involved in the representation of numerical magnitude. The IPS magnitude system underlies a "sense of number" by holding quantity in an abstract format, such as the "four-ness" that is common among the number notations "∷", "4", and "four". In a functional magnetic resonance imaging (fMRI) paradigm, Piazza and colleagues (Piazza et al., 2004; Piazza et al., 2007) showed that activity of neurons in the IPS decreases when a certain numerical quantity is repeatedly shown (a phenomenon known as "repetition suppression") but increases again on presentation of another quantity. The IPS activity increase was larger for quantities that were farther away from the adapted numerosity, which is in accordance with the distance effect found at the behavioral level. Similar to the behavioral variant, this neural distance effect has been observed in imaging studies for both non-symbolic (Piazza et al., 2004, 2007) and symbolic numbers (Piazza et al., 2007; Pinel et al., 2001). These results suggest that enculturated symbols map onto abstract internal analogue magnitude representations in the IPS (Verguts and Fias, 2004). In other words, the same IPS magnitude system appears to underlie the representation of numerical magnitude for both non-symbolic and symbolic numbers. Thus, if arithmetic problems are solved via magnitude calculations, the IPS is likely to be involved (Dehaene et al., 2004; for a similar argument, see Venkatraman et al., 2005).

Verbal retrieval of arithmetic facts from memory, on the other hand, appears to be facilitated by the left AG, together with neighboring perisylvian areas including the posterior superior and middle temporal gyrus, and the supramarginal gyrus (Cohen et al., 2000; Dehaene et al., 2004; Dehaene et al., 2003; Prado et al., 2011). Grabner et al. (2009) showed that self-reported arithmetic fact retrieval engages in stronger AG activity than self-reported procedural strategies. However, in contrast to the IPS regions which have been regularly implicated in magnitude calculations, a role for the left AG in arithmetic fact retrieval has been less consistently replicated (e.g., for a non-replication, see Rosenberg-Lee et al., 2011).

1.2.2. (Non-) specificity of IPS activity to numerical processing

A problem with using IPS activity as a reflection of magnitude calculations during mental arithmetic is that it is also observed during other mental processes. Within the numerical domain, the IPS appears to be active during detection of numbers even before the numbers are manipulated (Eger et al., 2003). Therefore, to relate IPS activity to the *mental manipulation* of magnitudes, that is the actual calculation, one has to control for number detection related IPS activity. Venkatraman et al. (2005) set out to investigate whether the addition process in itself (also called "mental addition") would activate the IPS in a notation independent manner. To overcome ambiguity in interpretation of the results, the authors included numbers in their control condition such that they could dissociate IPS activity due to the addition process from IPS activity related to perceiving numbers. They observed bilateral IPS activity for addition of both dots and Arabic numbers, which led them to conclude that mental addition involves the IPS independent of number notation. However, some