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Phonology and arithmetic in the language–calculation network

Josefine Andin [a,*], Peter Fransson [b], Jerker Rönnberg [a], Mary Rudner [a]

[a] Linnaeus Centre HEAD, Swedish Institute for Disability Research, Department of Behavioural Sciences and Learning, Linköping University, SE-581 83 Linköping, Sweden
[b] Department of Clinical Neuroscience, Karolinska Institute, SE-171 77 Stockholm, Sweden

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ABSTRACT

Arithmetic and language processing involve similar neural networks, but the relative engagement remains unclear. In the present study we used fMRI to compare activation for phonological, multiplication and subtraction tasks, keeping the stimulus material constant, within a predefined language–calculation network including left inferior frontal gyrus and angular gyrus (AG) as well as superior parietal lobule and the intraparietal sulcus bilaterally. Results revealed a generally left lateralized activation pattern within the language–calculation network for phonology and a bilateral activation pattern for arithmetic, and suggested regional differences between tasks. In particular, we found a more prominent role for phonology than arithmetic in pars opercularis of the left inferior frontal gyrus but domain generality in pars triangularis. Parietal activation patterns demonstrated greater engagement of the visual and quantity systems for calculation than language. This set of findings supports the notion of a common, but regionally differentiated, language–calculation network.

1. Introduction

A connection between language and arithmetic has been suggested in both behavioral (De Smedt, Taylor, Archibald, & Ansari, 2010; Dehaene, Piazza, Pinel, & Cohen, 2003; Lee & Kang, 2002) and imaging studies (Benn, Zheng, Wilkinson, Siegal, & Varley, 2012; Venkatraman, Siong, Chee, & Ansari, 2006), in line with recent models of complex mental processing (Fehr, 2013). Language processing has been suggested to follow two main neural streams which constitute the perisylvian language network; a ventral stream for speech comprehension and a dorsal stream for sensory–motor integration (Hickok & Poeppel, 2007; Rauschecker & Scott, 2009). Neural representations of phonological processing have been found in a left lateralized fronto-temporo-parietal network encompassing the posterior part, pars opercularis, and the anterior part, pars triangularis, of the left inferior frontal gyrus (lIFG), as well as the left angular gyrus (lAG) and the left supramarginal gyrus (lSMG). During rhyme judgement, a prototypical test of phonological processing, lIFG has been shown to be engaged in sensory–motor integration, decoding and covert articulation (Burton, LoCasto, Krebs-Noble, & Gullapalli, 2005), and several studies have dissociated phonological processing in pars opercularis from semantic processing in pars triangularis (McDermott, Petersen, Watson, & Ojemann, 2003; Poldrack et al., 1999; Vigneau et al., 2006). The lAG has been shown to be involved in mapping between phonological and orthographic representations (Booth et al., 2004) while the role of the lSMG seems to be mainly sensory–motor integration (Hickok & Poeppel, 2007; McDermott et al., 2003; Rauschecker & Scott, 2009). Further, the left superior parietal lobule (SPL) has been implicated in phonological processing (Shivde & Thompson-Schill, 2004), as well as the processing of linguistic structures (Monti, Parsons, & Osherson, 2012) and linguistic inference (Monti, Parsons, & Osherson, 2009), extending the perisylvian language network posteriorly.

According to one of the most influential models of numerical cognition, the triple code model (Dehaene, 1992; Dehaene & Cohen, 1995), three different representational systems are recruited in number processing: Numbers are encoded as strings of Arabic numerals within a *visual system*, these numerals are represented verbally within the *verbal system* and the magnitude of the numbers is represented in the *quantity system*. Recent work has suggested that the visual system also extends to include the SPL bilaterally which has been shown to be engaged during orientation of spatial attention (Dehaene et al., 2003) and may be involved in e.g. number comparisons (Pinel, Dehaene, Rivière, & LeBihan, 2001), approximation (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999) and counting (Piazza, Mechelli, Butterworth, & Price, 2002).

The verbal system is suggested to be located in lAG (Dehaene et al., 2003). This system is thought to be concerned with the

* Corresponding author.
E-mail addresses: josefine.andin@liu.se (J. Andin), peter.fransson@ki.se (P. Fransson), jerker.ronnberg@liu.se (J. Rönnberg), mary.rudner@liu.se (M. Rudner).

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verbal coding of numbers and it has been shown that the more calculation tasks require verbal processes, such as arithmetic fact retrieval, the more the system is activated. For example, more activation has been found for exact calculation compared to approximate calculation (Dehaene et al., 1999) and for multiplication compared to subtraction (Chochon, Cohen, van de Moortele, & Dehaene, 1999; Lee, 2000).

The horizontal portion of the intraparietal sulcus bilaterally, has been associated with the quantity system, and suggested as a candidate region for number specificity (Dehaene et al., 2003). It is also thought to be involved in magnitude manipulation using a mental analogue number line (Piazza et al., 2002). Activation in this region has been reported for non-verbal representations (Dehaene et al., 2003; Piazza et al., 2002) and it responds more for number words compared to non-number words (Dehaene & Cohen, 1995). Further, it has been shown to be activated more for subtraction compared to multiplication (Chochon et al., 1999; Lee, 2000) and for approximate compared to exact calculation (Dehaene et al., 1999),

Behaviorally, it has been shown that language switching interferes with exact but not approximate calculation (Dehaene et al., 1999) and that simultaneous processing of a phonological task interferes with multiplication but not with subtraction (Lee & Kang, 2002), supporting the notion that the verbal system is recruited more for calculation tasks that put greater demands on verbal processing. Several imaging studies have also shown that calculation tasks in general and multiplication tasks in particular activate language related brain regions (Benn et al., 2012; Prado et al., 2011; Rickard et al., 2000; Zhou et al., 2007). Together these findings support the notion of a common language–calculation network with greater similarity between phonological processing and arithmetic when arithmetic fact retrieval is required, i.e. greater similarity between phonological processing and multiplication than between phonological processing and subtraction. However, although the same network has been reported for both phonological and arithmetical tasks, there is evidence of regional differences. In a study by Fedorenko, Duncan, and Kanwisher (2012), functional specificity of Broca's area was identified, showing that arithmetic is processed in the domain-general periphery rather than the language-specific core. Hitherto, the link between language and calculation has largely been examined implicitly by investigating brain activity elicited by calculation in areas that are generally known to be engaged in language processing (e.g. Benn et al., 2012; Delazer et al., 2003) or as defined by a phonological processing (Prado et al., 2011) or a sentence reading task (Fedorenko et al., 2012).

In the present study, we adopted a different approach by directly contrasting multiplication, subtraction and phonological processing in order to investigate differential engagement of a predefined language–calculation network. Importantly, we used the same stimulus material for all three experimental tasks as well as a visual control task and two cognitive control tasks, ensuring similar visual activation across tasks. This was achieved by presenting visual arrays of six characters, arranged in three digit-letter pairs (see Fig. 1). The arithmetic tasks involved determining whether a multiplication or subtraction problem could be constructed from the digits while the phonological task involved identifying a digit/letter pair whose lexical labels rhymed. The visual control task involved identifying whether there were two dots over any of the letters. Subtracting activation generated by this task allowed us to identify task-specific phonological and arithmetic activation not related to visual perception. The cognitive control task for the arithmetic tasks involved determining whether the digits in the array were in numerical order and the cognitive control task for the phonological task involved determining whether the letters in the array were in alphabetical order. Subtracting activation generated by these tasks allowed us to identify task-specific phonological and arithmetic activation not related to alphabetic and numeric ordering.

The language–calculation network was predefined by a mask including the seven regions of interest central to language and calculation: lIFG (BA44/45), lAG (BA39), bilateral SPL (BA7) and hIP. We predicted largely similar patterns of activation for all three tasks versus visual control throughout the language–calculation network, reflecting process similarities. In particular, we predicted a general activation for all three tasks versus visual control in lIFG,

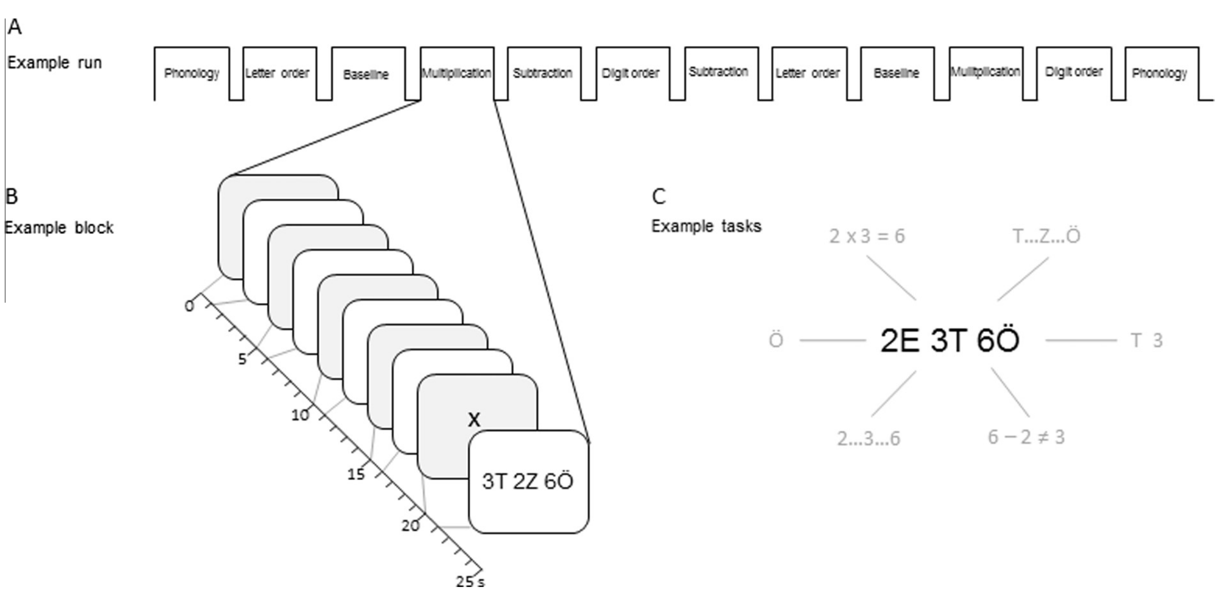

Fig. 1. Schematic representation of (A) a scanning run, (B) an example of stimulus display and timing within a block and (C) an overview of the different tasks: the multiplication task involved determining whether the product of any two of the digits equaled the third (i.e. $2 \times 3 = 6$) and subtraction whether the difference between any two of the digits equaled the third (no solution in the present example). In the phonology task the participants determined if the lexical labels of any of the three digit/letter pairs rhymed (i.e. 3T). The visual control task required identification of two dots over any of the letters (i.e. Ö). The cognitive controls (digit order and letter order) involved determining if the digits and letters are in order (i.e. 236 and ETÖ). Only characters in black are visible upon presentation.