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# How number line estimation skills relate to neural activations in single digit subtraction problems

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ABSTRACT

The Number Line (NL) task requires judging the relative numerical magnitude of a number and estimating its value spatially on a continuous line. Children's skill on this task has been shown to correlate with and predict future mathematical competence. Neurofunctionally, this task has been shown to rely on brain regions involved in numerical processing. However, there is no direct evidence that performance on the NL task is related to brain areas recruited during arithmetical processing and that these areas are domain-specific to numerical processing. In this study, we test whether 8- to 14-year-old's behavioral performance on the NL task is related to fMRI activation during small and large single-digit subtraction problems. Domain-specific areas for numerical processing were independently localized through a numerosity judgment task. Results show a direct relation between NL estimation performance and the amount of the activation in key areas for arithmetical processing. Better NL estimators showed a larger problem size effect than poorer NL estimators in numerical magnitude (i.e., intraparietal sulcus) and visuospatial areas (i.e., posterior superior parietal lobules), marked by less activation for small problems. In addition, the direction of the activation with problem size within the IPS was associated with differences in accuracies for small subtraction problems. This study is the first to show that performance in the NL task, i.e. estimating the spatial position of a number on an interval, correlates with brain activity observed during single-digit subtraction problem in regions thought to be involved in numerical magnitude and spatial processes.



## Introduction

Mathematical skill predicts later academic achievement more strongly than early reading and socio-emotional skills (Duncan et al., 2007; National Mathematics Advisory Panel, 2008). Therefore understanding individual differences has become a central research question for educational policies. Several studies suggest that differences in arithmetical performance are related to neural activations specific for numerical processing (De Smedt et al., 2011, 2013; Price et al., 2007).

A widely used numerical task that has shown to be predictive of future mathematical skill is the Number Line (NL) task (Booth and Siegler, 2006; Cowan and Powell, 2014; Siegler and Booth, 2004; Siegler and Opfer, 2003). This task requires both numerical magnitude and spatial processing since participants are asked to estimate the position of a given number (e.g., 21) onto a black horizontal line with the left and right ends labeled as 0 and 100 (or 1000), respectively. Younger children who have a less precise representation of numerical values overestimate small numbers and underestimate larger ones. Linearity is initially acquired for smaller ranges and progressively, with age and increasing number knowledge, linearity is extended to larger ranges (Berteletti et al., 2010; Siegler and Booth, 2004; Siegler et al., 2009). Performance on the NL task correlates with other estimation tasks (Booth and Siegler, 2006; Laski and Siegler, 2007), improves following interventions on children's linear and cardinal understanding of the numerical sequence (Ramani and Siegler, 2008; Siegler and Ramani, 2008), and is correlated with and is predictive of arithmetic learning and mathematical achievement (Booth and Siegler, 2008; Link et al., 2014; Linsen et al., 2014; Ostergren and Träff, 2013; Sasanguie et al., 2013; Schneider et al., 2009). Performance is also impaired or delayed in children with math learning difficulty (Geary et al., 2008; Landerl, 2013). Importantly, improving children's performance on the NL task enhances performance in numerical magnitude processing tasks as well as facilitates learning of multi-digit addition problems (Booth and Siegler, 2008; Kucian et al., 2011). Because the NL task has been shown to be a strong and unique predictor of arithmetical ability in grades 1 and 2 over and above other non-symbolic and symbolic tasks (Lyons et al., 2014), and because the NL tasks were correlated to mental multi-digit subtraction performance (Linsen et al., 2014), it can be argued that the NL task is specifically calling upon numerical processes

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that are crucial for later acquisition of mathematical competences. Two types of functional processes involved in the Number Line task might explain the relationship with mathematical performance and in particular with subtraction problems. First in both tasks, the symbolic numbers need to elicit the numerical magnitude representation. This allows for a comparison between the symbolic numbers: in the Subtraction task, the two digits need to be compared to determine the result; in the Number Line task, the number to position has to be compared to the numerical boundaries of the interval to determine it's relative numerical magnitude. Second, both tasks call upon visuo-spatial processes. For the Number Line task, the symbolic number that has to be estimated has to be translated into a visual segment. To do this, children need to focus first on the entire interval and then move their attention along the line to estimate the position. Subtraction tasks have also been shown to rely on visuo-spatial processes (Dehaene et al., 2003; Knops and Willmes, 2014; Knops et al., 2009; Rotzer et al., 2009), and visuo-spatial proficiency has been shown to predict arithmetic performance in children (De Smedt et al., 2009; Rotzer et al., 2009). This result may be explained by the observation that efficient strategies rely on mechanisms that involve shifts of spatial attention (Knops et al., 2009). Indeed, studies have shown that subtraction and addition problems lead to under- and over-estimation and this Operational Momentum effect has been explained in terms of attentional shifts on a spatially organized mental representation of numbers (Knops et al., 2009, 2013, 2014) as if quantities were represented in the format of an internal mental Number Line (Hubbard et al., 2005; Rotzer et al., 2009).

From a neurofunctional perspective, processing of numerical magnitudes has been identified in the parietal lobes and more specifically in the bilateral intraparietal sulcus (IPS; Ansari, 2008; Nieder and Dehaene, 2009; Piazza et al., 2004; Piazza et al., 2007; see Arsalidou and Taylor, 2011 for a meta-analysis). This area is sensitive to the distance effect in digit comparison tasks both for children and adults (Mussolin et al., 2010; Pinel et al., 2001) as well as being less sensitive in children with mathematical learning disability (Mussolin et al., 2010). The IPS is also found to be more active in calculation tasks compared to reading numerical symbols (Burbaud et al., 1999; Chochon et al., 1999; Pesenti et al., 2000), and more active for larger compared to smaller arithmetical problems (Ashkenazi et al., 2012; De Smedt et al., 2011). Moreover, the IPS shows greater activation during subtraction than multiplication (Chochon et al., 1999; Ischebeck et al., 2006; Prado et al., 2011, 2014) likely due to the fact that subtraction problems rely more on calculation procedures (Fayol and Thevenot, 2012) and quantity processing compared to multiplication problems (Dehaene et al., 2003; Prado et al., 2011, 2014).

Another parietal area often active in tasks requiring numerical manipulation is the posterior superior parietal lobule (PSPL) with mesial extension into the precuneus (PCu; Arsalidou and Taylor, 2011; Dehaene et al., 2003; Kaufmann et al., 2011). This area is active during number comparison (Pesenti et al., 2000; Pinel et al., 2001), approximation (Dehaene et al., 1999), subtraction of two digits (Knops et al., 2009; Lee, 2000), and counting (Piazza et al., 2002). Increased activation is found for more complex operations (Menon et al., 2000), and for subtraction problems compared to multiplication problems (Prado et al., 2011, 2014). However, this region also plays a role in several visuospatial tasks such as reaching, grasping, eye and/or attention orienting, mental rotation, and spatial working memory (Hubbard et al., 2005; Knops et al., 2009; Simon et al., 2002, 2004). Knops et al. (2009) investigated the relation between eye movement and arithmetic processing in adults using fMRI. They trained a multivariate classifier on saccade-related activity in the PSPL and were able to predict the type of mental operation (i.e., addition of subtraction), irrespective of notation (i.e., symbolic or non-symbolic). The authors suggest that mental arithmetic recruits parietal areas that are associated with visuospatial processing and that mental calculation may (at least partially) rely on the dynamic interplay between subsystems of the parietal cortex (i.e., IPS and PSPL).

On the one hand, imaging studies indicate that different subsystems in the parietal cortex (i.e., IPS for numerical magnitude and PSPL for visuospatial components of numerical and arithmetical processing) support mental calculation and, on the other hand, performance in the NL task is correlated and predictive of future arithmetic skill. However, to our knowledge, there is no direct evidence that estimating the position of a number on a line is related to functional areas used for calculation. Only two studies investigate the neural bases of the NL task. The first study investigated whether an intervention program using a NL-like game induces neurofunctional changes in areas involved in judging the relative magnitude of digits (Kucian et al., 2011). The game was intended to improve both estimation and arithmetical skills (i.e., numbers, sets of dots and arithmetical results had to be positioned on lines) in 9-year-old children with and without mathematical difficulty. Performance in the NL task was significantly improved for both groups. Using fMRI, children were required to judge whether triplets of digits were in ascending order. Training resulted in decreased activation in left IPS along with frontal areas, suggesting an increased efficiency in performing the task. Although these results support the effectiveness of the intervention, the authors showed improvement in magnitude judgment and not in arithmetical processing. The second study, using fMRI, investigates the brain regions involved during a classical NL task and a brightness estimation line task (i.e., continuous magnitude judgment) using shades of gray (Vogel et al., 2013). Results indicated some overlap in the right posterior part of IPS but, most importantly, the bilateral anterior part of IPS was specifically recruited for estimating symbolic numbers. This study is the first that directly investigates the NL task in an imaging paradigm and shows activations in areas typically involved in numerical magnitude processing. Unfortunately, no direct relation between these activations and arithmetical performance was investigated.

In the present study, we test whether performance on the NL task is related to activation found during simple arithmetical processing and if this relation relies on domain-specific processes. This would bring neuro-functional evidence to the behavioral relation found between performance to the NL task and arithmetic skill. We therefore collected behavioral performance on the NL task and functional (fMRI) data during a single-digit Subtraction task in 8- to 14-year-old children. In this age range, arithmetical learning and estimation abilities are still improving (e.g., Holloway and Ansari, 2009; Siegler and Booth, 2004) increasing the chance of observing a relation between the two tasks. We chose single-digit subtraction problems because they have shown to rely more on quantitative manipulation compared to other arithmetical operations (Dehaene, 1992; Dehaene et al., 2003; Fayol and Thevenot, 2012; Prado et al., 2014, 2001). In support of this, the symbolic distance effect, that is the ability to determine which of two digits is numerically larger, was found to be specifically related to subtraction problems in children (Lonnemann et al., 2011). To isolate domain-specific areas involved in numerical processing, participants were also asked to perform a numerosity judgment task in the scanner (i.e., numerical comparison of sets of dots). Parietal areas activated by this task were then used as regions of interest (ROI) to investigate the relation between performance on the NL task and activation to the Subtraction task. Indeed, the parietal cortex, and specifically the IPS, has shown modulation of activation specifically to changes in numerical information (Cantlon et al., 2006; Piazza et al., 2004).

Within the numerical processing areas, we expected to find a significant relation of performance on the NL task with bilateral IPS activation. The IPS responds specifically to magnitude information required in both the NL task and the Subtractions task (Piazza et al., 2004). Specifically, we expected children with better NL estimation abilities to show greater activation for larger compared to smaller problems (De Smedt et al., 2011; Stanescu-Cosson et al., 2000) indicating greater quantity manipulation for more effortful and less well learned problems. Because children in our study are still learning, only small problems are likely to be adequately mastered thus showing less activation compared to