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The effect of visual parameters on neural activation during nonsymbolic number comparison and its relation to math competency

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ABSTRACT

Nonsymbolic numerical comparison task performance (whereby a participant judges which of two groups of objects is numerically larger) is thought to index the efficiency of neural systems supporting numerical magnitude perception, and performance on such tasks has been related to individual differences in math competency. However, a growing body of research suggests task performance is heavily influenced by visual parameters of the stimuli (e.g. surface area and dot size of object sets) such that the correlation with math is driven by performance on trials in which number is incongruent with visual cues. Almost nothing is currently known about whether the neural correlates of nonsymbolic magnitude comparison are also affected by visual congruency. To investigate this issue, we used functional magnetic resonance imaging (fMRI) to analyze neural activity during a nonsymbolic comparison task as a function of visual congruency in a sample of typically developing high school students ($n = 36$). Further, we investigated the relation to math competency as measured by the preliminary scholastic aptitude test (PSAT) in 10th grade. Our results indicate that neural activity was modulated by the ratio of the dot sets being compared in brain regions previously shown to exhibit an effect of ratio (i.e. left anterior cingulate, left precentral gyrus, left intraparietal sulcus, and right superior parietal lobe) when calculated from the average of congruent and incongruent trials, as it is in most studies, and that the effect of ratio within those regions did not differ as a function of congruency condition. However, there were significant differences in other regions in overall task-related activation, as opposed to the neural ratio effect, when congruent and incongruent conditions were contrasted at the whole-brain level. Math competency negatively correlated with ratio-dependent neural response in the left insula across congruency conditions and showed distinct correlations when split across conditions. There was a positive correlation between math competency in the right supramarginal gyrus during congruent trials and a negative correlation in the left angular gyrus during incongruent trials. Together, these findings support the idea that performance on the nonsymbolic comparison task relates to math competency and ratio-dependent neural activity does not differ by congruency condition. With regards to math competency, congruent and incongruent trials showed distinct relations between math competency and individual differences in ratio-dependent neural activity.

1. Introduction

Several large-scale, longitudinal studies indicate that math skills at school entry are a strong predictor of later academic achievement (Duncan et al., 2007; Geary et al., 2013) and socioeconomic status (Ritchie and Bates, 2013). Measured later in life, they are linked to employment status (Goodman et al., 2015) and even physical and mental health (Parsons and Bynner, 2005). In an effort to understand individual differences in math ability, much research has focused on the perception of numerical magnitudes. As a result, it has been well established that individual differences in the processing of numerical magnitude correlate with and predict later math achievement (Chen and Li, 2014; Schneider et al., 2016). And yet, the neural mechanisms underlying the link between processing of numerical magnitude and more advanced mathematical thought remain poorly understood.

Our understanding of this link relies on a relatively small set of

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experimental paradigms, most notably an array of nonsymbolic number comparison tasks, whereby a participant judges which of two groups of objects, such as dots or squares, is more numerous. Performance on this task is often assumed to reflect the precision of a mental representation of numerical magnitude (Halberda et al., 2008). Already, diagnostic tools for math learning disability (Butterworth and Laurillard, 2010; Nosworthy et al., 2013) and early learning interventions (Szűcs and Myers, 2016) are being developed which target measurement of and training of the nonsymbolic number system. However, in light of recent findings, these efforts may be premature. At least three behavioral studies have reported that unintended consequences of controlling the visual parameters of stimuli in the nonsymbolic comparison task have a significant influence on the relationship between task performance and math achievement (Bugden and Ansari, 2015; Fuhs and McNeil, 2013; Gilmore et al., 2013), thus complicating the link between magnitude perception and math. In other words, it is currently unclear whether the mechanism linking nonsymbolic comparison performance and math is in fact the precision of magnitude representation, or rather alternative cognitive mechanisms related to the processing of visual stimulus parameters. In order to understand the link between this potential confound in the nonsymbolic comparison task, the basic systems that encode numerical magnitude in the brain, and their link to math achievement, a detailed understanding of the neural mechanisms underlying the influence of visual cues on the perception of numerical magnitudes is essential. With this understanding, diagnostic tools and interventions may target specific neurocognitive mechanisms underlying math skills. Without it, they are at risk of targeting behaviors that merely correlate with math achievement but are not fundamental to its development.

1.1. *Numerical magnitude processing efficiency & math competency*

Most models of numerical magnitude perception begin with object identification that then feeds into a summation code, which abstracts number of objects over object position (see Nieder, 2016; for a review). The summation code then feeds into a number-selective code where populations of neurons in the superior parietal lobe have Gaussian response functions with peaks tuned to specific magnitudes (Nieder and Dehaene, 2009; Verguts and Fias, 2004). This number-selective code forms the basis of the “Approximate Number System” (ANS, Dehaene, 1997). Accordingly, numbers that are closer together in magnitude have more overlapping neural representation compared to numbers that are further apart, which are thought to be more distinct in neural representation. As a result, people are slower and less accurate when discriminating between numbers that are closer together in numerical magnitude versus those that are further apart. This ‘ratio effect’ can be modeled as a function of the numerical ratio between number pairs (Piazza et al., 2004). Therefore, in principle, to measure individual differences in this system's acuity, one need only measure the degree of overlap in the distribution of neighboring magnitude response functions. The nonsymbolic number comparison task attempts to do this by measuring accuracy rates and response times as participants judge which of two groups of objects is more numerous. In general, a smaller effect of ratio on accuracy and reaction time, or even simply higher accuracy rates and lower response times, are thought to indicate increased precision of the ANS (De Smedt and Gilmore, 2011).

Beginning with a retrospective study by Halberda, Mazzocco, & Feigenson (Halberda et al., 2008) that linked performance on the nonsymbolic number comparison task in 9th grade to math achievement in Kindergarten through 6th grade, a number of studies have supported the claim that ANS acuity is related to math abilities ranging from counting to arithmetic to algebra (Chen and Li, 2014; Schneider et al., 2017) and that reduced ANS acuity may represent a core deficit in the math learning disability developmental dyscalculia (Mazzocco et al., 2011; Piazza et al., 2010). Several neuroimaging studies also provide evidence for this link. For example, compared to typically developing children, children with dyscalculia show less modulation due to numerical magnitude in the right intraparietal sulcus (IPS) (Price et al., 2007), a region that has consistently been linked to numerical magnitude encoding (Sokolowski et al., 2016). Atypical activation patterns in other brain regions during this task have also been associated with dyscalculia including parieto-occipital regions (Dinkel et al., 2013), supplementary motor area and fusiform gyrus (Kucian et al., 2011), and inferior parietal regions (Kaufmann et al., 2009). Further, neural correlates of the ratio effect during nonsymbolic numerical comparison have also been linked to individual differences in math achievement in a typically developing population (Gullick et al., 2011), though in the study by Gullick and colleagues, the neural ratio effect is negatively correlated with math.

1.2. *Confounding factors from visual controls*

Although the research discussed above points to a link between ANS acuity, as indexed by nonsymbolic number comparison performance, and math ability, recent research suggests that the relationship may be related to processes other than ANS acuity alone. To ensure that participants respond to number comparison trials on the basis of numerosity rather than other visual cues that often covary with numerosity, such as surface area or density, researchers regularly control for these visual cues. The most common method of control is to create stimuli in which the surface area of the dots is either congruent with the correct choice (i.e. the dot set with the larger surface area is the dot set with the larger numerosity) or incongruent (i.e. both dot sets have the same surface area and the more numerous dot set has smaller dots) (Dehaene et al., 2005). Behavioral studies show that when selecting the larger of two sets, performance is significantly influenced by non-numeric visual properties of the stimulus such that individuals are slower to respond and less accurate in the face of incongruent visual information (Gebuis and Reynvoet, 2012; Szűcs et al., 2013). One theory posits that these non-numeric visual cues require participants to inhibit their visually-based response before making a quantity-based judgment (Clayton and Gilmore, 2014). Both Gilmore et al. (2013) and Fuhs and McNeil (2013) found that only performance on incongruent trials of the nonsymbolic number comparison task was related to symbolic math achievement, in primary school and preschoolers respectively. In both studies, this correlation was no longer significant after controlling for inhibitory control measured during tasks not related to numerical magnitudes. In a study of individuals with dyscalculia, Bugden and Ansari (2015) showed that differences in ANS acuity between dyscalculic and typically developing children were only found when analyzing incongruent trials of the nonsymbolic number comparison task. Though inhibitory control was not measured, Bugden & Ansari's results showed a close relationship between visuo-spatial working memory and performance on incongruent trials only in individuals with dyscalculia, indicating that working memory function during incongruent trials may be important for the relationship between nonsymbolic comparison and math. The results of these three studies indicate that the link between performance on nonsymbolic comparison tasks and math achievement may be explained by cognitive processes used to extract numerical magnitude from stimuli in the face of conflicting visual information rather than simply the representational acuity of the ANS.

Recent neuroimaging evidence of the nonsymbolic comparison task indicates that recruitment of neural resources also differs as a function of congruency condition. In a study of typically developing adults, Leibovich et al. (2015) showed that incongruent trials are associated with greater activity in the superior frontal gyrus and left inferior/middle frontal gyri, but less activity in the right middle temporal and posterior cingulate gyri, than congruent trials. However, Leibovich et al. (2015) examined activation during numerical versus non-numerical processing as a function of congruency, as opposed to examining the effect of congruency on ratio-dependent task activity. In order to investigate how differences in congruency specifically relate to processing of numerical information, the effect of congruency on magnitude-specific activation must be evaluated. Just as a behavioral ratio effect has become a