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MATHEMATICAL COGNITION IN CHILDREN: EVIDENCE FROM FMRI

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Abstract. Mathematics is a main subject in school curriculum and typically developing children learn quickly how numbers and quantities relate to each other. Mathematical performance improves dramatically during childhood and adolescence. Although functional magnetic resonance imaging (fMRI) studies with children are accumulating, a clear understanding of brain areas that underlie key mathematical processes is still lacking. Eligible fMRI studies that examine mental arithmetic with children were identified and contrast coordinates were selected based on whether the experimental paradigm was related to either number tasks (i.e., numerical processing without having prescribed operations such a distance effects) or calculation tasks (i.e., formal mathematical operations such as addition and subtraction). Activation Likelihood Estimate (ALE), is a meta-analytic method used to generate 3D maps indicating the likelihood of activation within a given voxel of a template brain. Results show concordance of brain activity in core areas related to mental arithmetic, such as the parietal and prefrontal regions, with clear distinctions between number and calculation tasks. Notable findings are the involvement of the insular cortices, an area that has not been highlighted in this type of cognition. A topographical atlas of mathematical processes in typically developing children is proposed.

Keywords: mathematical cognition, children, fMRI, meta-analyses, insula

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Behavioral research shows that mathematical performance is affected by many factors including motivation (Steinmayr, Spinath, 2009), intelligence (Mayes et al., 2009), and educational background (Opdenakker, Van Damme, 2007; Cragg, Gilmore, 2014). Mathematical performance is also related to core cognitive abilities such as working memory and mental attention (e.g., Agostino et al., 2010; Pascual-Leone et al., 2010). Mental attention is the maturational component of working memory responsible for boosting and manipulating task-relevant processes and information in the mind (Pascual-Leone, 1970; Arsalidou et al., 2010; Pascual-Leone, Johnson, 2011). Therefore, mathematical proficiency critically relies on the ability to manipulate, boost or inhibit, and update schemes (i.e., information-bearing processes). Scheme units are important, because problem solving is not just a matter of storing information in executive-controlled ways or practicing inhibition control (Cragg, Gilmore, 2014); it also requires that the appropriate representational and action/operative schemes be available. Such processes have been associated with activity in the prefrontal cortex (e.g., Arsalidou et al., 2013). Research shows that the prefrontal cortex has protracted development (e.g., Gogtay et al., 2004) during a growth period that coincides with advances in mathematical abilities in children. The prefrontal cortex is a key brain region, concordant across mathematical-cognition studies in healthy adults (see Arsalidou, Taylor, 2011, for meta-analyses). Much progress has been made in understanding the brain correlates of mathematical cognition in adults; however, little is known about these processes in children. This paper compiles data from functional magnetic resonance imaging (fMRI) studies and reports concordant brain activity in typically developing children when solving math tasks with and without formal calculations (i.e., operations).

The literature was searched with a combination of key terms such as *children*, *fMRI*, *arithmetic*, *calculation*, *math,* and *numerical*. This search yielded more than 100 articles that were screened for eligibility. Specifically, articles needed to (a) have used fMRI and used tasks involving numbers and/or calculations, (b) have reported whole-brain within-group results on healthy child participants, (c) have used random-effects analyses, and (d) have reported coordinates either in Talairach or Montreal Neurological Institute (MNI) coordinate space. Lastly, the studies were screened for age so that we included studies that tested children who were 14 years old or younger.

Activation Likelihood Estimate (ALE) is a powerful method for identifying over-arching patterns in findings across fMRI studies (Turkeltaub et al., 2002; Eickhoff et al., 2009, 2012, 2017; freely available at http://brainmap.org/ale/). Unlike traditional systematic reviews of the literature, ALE uses contrast coordinates from different studies to generate 3D maps that quantitatively indicate the likelihood that an area in the brain will be active compared to a random spatial distribution. Data from a total of 31 articles were included in two meta-analyses, one for number tasks and another for calculation tasks. Number tasks were classified as those that include numerical processing without any formal mathematical operations, such as quantity discrimination in dot patterns. Calculation tasks were classified as those that include formal mathematical operations such as multiplication, addition and subtraction.

Results show that when solving number tasks children show concordant brain activity in the right hemisphere including the inferior parietal lobule, inferior frontal gyrus, the claustrum and the insula. When solving calculation tasks children show concordant activity in various parietal areas including the angular gyrus, inferior parietal lobule and precuneus. Other areas include the right cingulate gyrus and insula and the left middle frontal gyrus, superior frontal gyrus and claustrum.

Children activate a set of areas in parietal and frontal brain regions comparable to those of adults (Arsalidou, Taylor, 2011), distinct however is concordant activity found in brain areas such as the insula and claustrum. Although prefrontal and parietal areas known for their involvement in executive and visual-spatial processes, respectively, have been previously acknowledged in models of mathematical cognition (e.g., Dehaene, Cohen, 1997), the insula and claustrum have not been directly linked to mathematical problem solving. Theoretical contributions of the findings will be discussed in the context of past models of mental arithmetic (Dehaene, Cohen, 1997; Arsalidou, Taylor, 2011) and in terms of the constructivist developmental theory (Pascual-Leone, 1970; Arsalidou, Pascual-Leone, 2016). For example, the hemispheric implication based on mathematical problem type (i.e., number tasks-right prefrontal and calculation tasks-left prefrontal) is consistent with the right-left-right model that explains hemispheric dominance as a function of the interaction between the mental demand of the task and the mental-attentional capacity of the individual (Arsalidou, Pascual-Leone, 2016). Practically, stereotaxic coordinates can serve as a topographical atlas for future studies of mathematical pro cesses in children.

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Математическое познание у детей: данные фМРТ

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Аннотация. Математика является главным предметом в школьном учебном плане, и дети с нормальным развитием быстро учатся понимать, как связаны между собой числа и различные величины. Результаты в математике значительно улучшаются в период детства и юношеского возраста. Хотя исследования детей, проведенные с помощью использования функциональной магнитно-резонансной томографии (фМРТ), проводятся все чаще и аккумулируют важные знания, все еще нет ясного понимания тех зон мозга, которые отвечают за ключевые математические процессы. Были отобраны фМРТ исследования, изучающие арифметические способности у детей, и были выбраны координаты на контрастов для двух видов экспериментальных парадигм: либо с заданием с цифрами (а именно обработка цифр без предписанных операций, таких как сравнение численных значений между собой), либо заданий на вычисление (формальные математические операции, как, например, сложение и вычитание). Вероятностная оценка активации (Activation Likelihood Estimate (ALE)) — мета-аналитический метод, используемый для генерирования 3D карт, показывающих вероятность активации в пределах рассматриваемого воксела модели мозга. Результаты показывают соответствие активности мозга в основных зонах, связанных с арифметическими способностями детей, таких как теменная и префронтальная области, с четким разграничением между заданиями с цифрами и заданием с вычислениями. Значимым является открытие вовлеченности островковой коры, зоны, роль которой не была подчеркнута в такого вида познании. Предлагается топографический атлас математических процессов у детей с нормальным развитием.

Ключевые слова: математическое познание, дети, фМРТ, мета-анализ, островковая кора

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