ARTICLE IN PRESS

Developmental Cognitive Neuroscience xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Developmental Cognitive Neuroscience

journal homepage: www.elsevier.com/locate/dcn

Brain areas associated with numbers and calculations in children: Meta-analyses of fMRI studies

Marie Arsalidou[a,b,*], Matthew Pawliw-Levac[a], Mahsa Sadeghi[a], Juan Pascual-Leone[a]

[a] Department of Psychology, Faculty of Health, York University, Toronto, Canada
[b] Department of Psychology, National Research University Higher School of Economics, Moscow, Russian Federation

A R T I C L E I N F O

Keywords:
Mathematical cognition
Meta-analyses
fMRI
Children
Development
Insula

A B S T R A C T

Children use numbers every day and typically receive formal mathematical training from an early age, as it is a main subject in school curricula. Despite an increase in children neuroimaging studies, a comprehensive neuropsychological model of mathematical functions in children is lacking. Using quantitative meta-analyses of functional magnetic resonance imaging (fMRI) studies, we identify concordant brain areas across articles that adhere to a set of selection criteria (e.g., whole-brain analysis, coordinate reports) and report brain activity to tasks that involve processing symbolic and non-symbolic numbers with and without formal mathematical operations, which we called respectively number tasks and calculation tasks. We present data on children 14 years and younger, who solved these tasks. Results show activity in parietal (e.g., inferior parietal lobule and precuneus) and frontal (e.g., superior and medial frontal gyri) cortices, core areas related to mental-arithmetic, as well as brain regions such as the insula and claustrum, which are not typically discussed as part of mathematical problem solving models. We propose a topographical atlas of mathematical processes in children, discuss findings within a developmental constructivist theoretical model, and suggest practical methodological considerations for future studies.

From an early age we learn to live in a world with numbers: on classroom doors, street signs, price tags, our phones, on our work activities. Typically we learn how numbers and quantities relate to each other (e.g., smaller, larger) from an early age; and most of us received some formal training in math, starting from grade school. Grade school training in mathematics coincides with protracted development of the pre-frontal cortex (e.g., Gogtay et al., 2004). The pre-frontal cortex is a key brain region, concordant across mathematical-cognition studies in healthy adults (Arsalidou and Taylor, 2011, for meta-analyses). Much progress has been made in understanding brain correlates of mathematical cognition; however, despite the increase in the studies examining children's mathematical problem solving (i.e., quantity discrimination and mathematical operations), a neuropsychological model for children is still not available. We have compiled data from functional magnetic resonance imaging (fMRI) studies and report concordant findings on brain correlates of typically developing children when solving math tasks with and without formal calculations (i.e., operations).

Behavioral protocols with children can be designed using math tasks such as printing or naming numbers, counting and sorting objects (Agostino et al., 2010; LeFevre et al., 2009). Neuroimaging tasks, however, are largely restricted to the visual domain, because they need to adhere to constraints/limitations of the imaging methodology (Kotsoni et al., 2006; Arsalidou and Im-Bolter, 2016; Arsalidou and Pascual-Leone, 2016). For fMRI studies, task protocols must be as time limited as possible. For instance, stimulus presentation should be brief, a few seconds; longer intervals are harder to control for irrelevant intruding processes (e.g., mind wandering). Manual responses are preferable to verbal responses, being less likely to produce head motion that compromise image quality. Moreover, calculation tasks are typically simple, often 1- or 2- digit operations, so that participants can provide a response within a limited time frame. Most fMRI studies that examine brain correlates of mathematical cognition, either in children or adults, follow these basic task characteristics.

The majority of fMRI studies in the literature investigated mathematical cognition in adults (e.g., Menon et al., 2000; Fehr et al., 2007), and the parietal lobes received the most attention in early studies of mental arithmetic. Indeed, parietal brain regions, such as bilateral intraparietal sulci, left angular gyrus, and bilateral superior parietal cortices, play distinct roles in number processing (Dehaene et al., 2003). Although the parietal cortex is fundamental to process mathematical problems, other regions are involved as well (Ansari et al.,

* Corresponding author at: Behavioural Science Building, York University, 4700 Keele Street, Toronto, Ontario, M3J 1P3, Canada.
E-mail address: marie.arsalidou@gmail.com (M. Arsalidou).

http://dx.doi.org/10.1016/j.dcn.2017.08.002
Received 27 January 2017; Received in revised form 5 July 2017; Accepted 2 August 2017

2005; Ischebeck et al., 2009; Zago et al., 2008; Zhou et al., 2007). Coordinate-based meta-analyses of 53 adult fMRI studies show areas, such as cingulate gyri, insula and the prefrontal cortex that are concordantly active in tasks of numbers and calculation (Arsalidou and Taylor, 2011).

Number tasks are those that contain numbers (e.g., viewing different digits) and quantities (e.g., viewing small or large arrays of dots), but require no formal calculation (e.g., multiplication). They have in common some sort of semantic judgement on numbers or quantities based on stipulated rules. *Calculation tasks* require as well operation rules, such as addition, subtraction and multiplication, applied to numbers. Distinct and common brain areas are active in adults during number and calculation tasks (Arsalidou and Taylor, 2011). Specifically, they elicit brain responses within regions such as inferior parietal lobule and inferior frontal cortex; however, calculations also recruit prefrontal areas, particularly in middle and superior frontal gyri (Arsalidou and Taylor, 2011).

The first fMRI study with children was published 16 years ago, by Eliez et al. (2001), testing children with or without a velocardiofacial syndrome, on an arithmetic task. fMRI studies of children working on mathematical problems are gradually increasing. As in adult studies, tasks administered to children divide into those investigating numerical processes (e.g., Ansari et al., 2005; Ansari and Dhital, 2006; Cantlon et al., 2006; Klien et al., 2014) and those studying mathematical operations (e.g., Ashkenazi et al., 2012; Davis et al., 2009a; Du et al., 2013; Metcalfe et al., 2013).

Studies that examine numerical processes typically ask children to select the larger number in a set of numbers (e.g., Ansari et al., 2005). The numbers in the set can differ by either small differences/distance (i.e., 1, 2 and 3) or large (i.e., 5, 6, and 7) ones. When the difference is small, children show activity in the superior parietal lobe, medial and inferior frontal gyri, the insula, and subcortical regions − mostly in the right hemisphere (Ansari et al., 2005). A subsequent study by the same researchers shows that when number differences are large, children activate the left hemisphere's dorsolateral prefrontal cortex, inferior frontal gyrus, and intraparietal sulcus (Ansari and Dhital, 2006). Other studies compared brain responses to numbers versus responses to shapes (Cantlon et al., 2006); or examined numerical processes versus a control task (Kaufmann et al., 2008).

Procedural differences in mathematical operations often lead to activity in different cortical regions (Kawashima et al., 2004; Prado et al., 2014). Studies examining various operations in the same children are important: Prado et al. (2014) examined brain responses to subtraction and multiplication, and Kawashima et al. (2004) examined three mathematical operations, addition, subtraction and multiplication. They found several common brain regions associated with them all. In the prefrontal cortex, for instance, addition and subtraction recruit the left middle frontal cortex, whereas multiplication recruits left middle and inferior frontal cortices (Kawashima et al., 2004); further, unlike addition and multiplication, subtraction elicited activity in the right intraparietal sulcus. More fMRI studies are needed that examine multiple mathematical operations in the same children.

A meta-analysis by Houdé et al. (2010) reports concordance across seven fMRI studies, which tested children with either number or calculation tasks, in right inferior and middle frontal gyri, left superior frontal gyrus and left middle occipital gyrus. This meta-analysis supports the view that prefrontal regions play an important role in mathematical cognition (Rivera et al., 2005; Ansari, 2008; Arsalidou and Taylor, 2011). Houdé et al. (2010) did not detect extensive involvement of parietal cortex, which is critical in mathematical cognition, possibly because of variability in the original studies' methodology and the low number of foci. Another meta-analysis examined 19 fMRI studies that included children (Kaufmann et al., 2011). Perhaps due to the low number of studies, the authors (Kaufmann et al., 2011) chose to include studies with fixed effects analyses (e.g. Kaufmann et al., 2006; Chen et al., 2006), coordinates from contrasts with variable performance (i.e., interaction of brain activity of high and low performers, Kovas et al., 2009), and variable age (i.e., coordinates resulting from a conjunction analysis between children and adults, Holloway and Ansari, 2010); they also included age ranges spanning over participants older than 18 years (i.e., 8.53–19.03 years, Rivera et al., 2005). Although such approach increases the number of studies and coordinates in the meta-analyses, it obscures the reliability of results.

Targeted meta-analyses were recently performed to identify brain correlates of number processing and notation (i.e., symbolic vs non-symbolic) in adults (Sokolowski et al., 2017) and children (Kersey and Cantlon, 2017). These studies suggest a network of parietal and frontal areas that underlie symbolic and non-symbolic processes. Based mainly on adult data theoretical models of mathematical cognition (e.g., Dehaene and Cohen, 1997; Arsalidou and Taylor, 2011) may not be suitable for accounting for developmental data (Arsalidou and Pascual-Leone, 2016). Also, it is challenging to identify developmental theories of cognition that make clear neural predictions on mathematical processes. We used a domain general cognitive theory of development for hypotheses building. The Theory of Constructive Operators (Pascual-Leone, 1970; Pascual-Leone and Johnson, 2005; Arsalidou and Pascual-Leone, 2016) outlines brain correlates associated with schemes and operation types to predict performance. The theory of constructive operators would predict that brain responses to number and calculations tasks are not material-driven, but process-driven and vary with the trade-off between participants' mental-attentional capacity and the mental demand of the task. Specifically, this trade-off predicts that the right hemisphere is involved in processing of automatized schemes, whereas the left hemisphere is involved in processing problems that involve the child's mental-attentional capacity, and are not automatized yet (details on this account is given in the discussion). Thus, we anticipated that number tasks should favour right frontal and parietal regions, whereas calculation tasks within the child's mental-attentional capacity will recruit additional frontal and parietal regions in the left hemisphere. In the current meta-analyses we explore brain areas involved in mathematical cognition of children younger than 14 years, and provide normative fMRI atlases in standard stereotaxic space for number and calculation tasks.

1. Methods

1.1. Literature search and article selection criteria

The literature was searched, in June 2017, by means of web-of-science (http://www.isiknowledge.com), using the terms fMRI and arithmetic and children; fMRI and calculations and children; fMRI and math and children; and fMRI and numerical and children. We have also added five papers using manual search. Fig. 1 shows the number of articles from this search, and the process we followed to identify eligible articles. Specifically, after eliminating duplicates, the articles were subjected to a series of selection criteria. For inclusion articles needed to: (a) be written in English, (b) have used fMRI and tasks involving numbers and mathematical operations; (c) have healthy children participants as the main or control group; (d) have reported whole-brain, within-group results using random-effects analysis; (e) have reported stereotaxic coordinates in Talairach or Montreal Neurological Institute (MNI) coordinates. Forty-three articles survived these criteria. To maintain data independence, we eliminated articles that reported contrast with analyses involving other age groups (e.g., conjunction between children and adults) and/or other tasks (e.g., conjunction between working memory and arithmetic problem solving). We also eliminated articles that included participants over 18 years in the children group (i.e., age range 8.53–19.03 years. Rivera et al., 2005; age range 7.7–21 years, Kesler et al. (2006); mean age 17 years 11.5 months, Price et al., 2013), and one article for including the same experiments (i.e., contrasts) using same participants in different publications (Meintjes et al., 2010a, 2010b). These controls resulted in 32