cortex 49 (2013) 2162–2177

Available online at www.sciencedirect.com

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Journal homepage: www.elsevier.com/locate/cortex

Research report

An electrophysiological investigation of non-symbolic magnitude processing: Numerical distance effects in children with and without mathematical learning disabilities

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ARTICLE INFO

Article history:
Received 2 October 2011
Reviewed 22 November 2011
Revised 22 February 2012
Accepted 22 November 2012
Action editor Mike Anderson
Published online 28 November 2012

Keywords:
Non-symbolic numerical comparison
Numerical distance effect
Children
Mathematical learning disabilities
EEG

ABSTRACT

Introduction: The aim of the present study was to probe electrophysiological effects of non-symbolic numerical processing in 20 children with mathematical learning disabilities (mean age = 99.2 months) compared to a group of 20 typically developing matched controls (mean age = 98.4 months).

Methods: EEG data were obtained while children were tested with a standard non-symbolic numerical comparison paradigm that allowed us to investigate the effects of numerical distance manipulations for different set sizes, i.e., the classical subitizing, counting and estimation ranges. Effects of numerical distance manipulations on event-related potential (ERP) amplitudes as well as activation patterns of underlying current sources were analyzed.

Results: In typically developing children, the amplitudes of a late parietal positive-going ERP component showed systematic numerical distance effects that did not depend on set size. For the group of children with mathematical learning disabilities, ERP distance effects were found only for stimuli within the subitizing range. Current source density analysis of distance-related group effects suggested that areas in right inferior parietal regions are involved in the generation of the parietal ERP amplitude differences.

Conclusion: Our results suggest that right inferior parietal regions are recruited differentially by controls compared to children with mathematical learning disabilities in response to non-symbolic numerical magnitude processing tasks, but only for stimuli with set sizes that exceed the subitizing range.

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http://dx.doi.org/10.1016/j.cortex.2012.11.009

1. Introduction

With a prevalence rate of around 7% (Gross-Tsur et al., 1996; Shalev, 2007), learning disabilities in the domain of numerical processing and arithmetic (i.e., mathematical learning disabilities – MLDs) are about as common as disabilities related to the acquisition of written language. But compared to the large number of scientific studies on reading impairments, research on MLDs is still in its infancy. However, approaches to remediation that focus on the critical conceptual and procedural underpinnings of MLD (for a review see Butterworth et al., 2011) can only be developed on the basis of a thorough understanding of the neurocognitive mechanisms underlying typical and impaired numerical cognition. This clearly calls for developmental and cognitive neuroscience to increase research efforts on both, basic numerical and higher-level abilities related to typical and atypical numerical processing functions, and their specific developmental trajectories (Ansari and Karmiloff-Smith, 2002).

One well-established experimental procedure to tap into the basic representation systems that can be assumed to underlie higher-level functioning in the domain of number processing is *non-symbolic numerical magnitude comparison*, a task paradigm that allows for systematic manipulations of quantity differences, i.e., the *numerical distance*, between the to-be-compared sets of items such as dot arrays. Originally described by Moyer and Landauer (1967), the impact of numerical distance manipulations on behavioral measures was taken to reflect basic characteristics of quantity processing functions. The most widely accepted model for the observed systematic increases of response latencies and error rates related to decreasing numerical differences between choices is the assumption of more representational overlap between close compared to far numerical values (Dehaene and Changeux, 1993; for an alternative model that implies conflict primarily at output levels, see Van Opstal et al., 2008). The fact that numerical distance effects were demonstrated to be both, format-general and modality-independent (Barth et al., 2003), and demonstrated not only in humans, but also in other species (Brannon and Terrace, 2000), was taken as evidence that manipulations of numerical distance tap into a pre-verbal mental representation of magnitude, i.e., an approximate number system that is thought to constitute a crucial start-up mechanism for the acquisition of abstract numerical knowledge (Butterworth, 2010; Piazza, 2010).

However, in cognitive and developmental psychology there is a long-standing debate on the existence of *qualitative* as opposed to mere *quantitative* functional differences between the processing of small and large numerosities (Feigenson et al., 2004). The majority of empirical evidence in support of the hypothesis that stimulus arrays of up to four items are apprehended by a specific mechanism that is categorically different from enumeration of larger set sizes, comes from chronometric studies (Kaufman et al., 1949; Mandler and Shebo, 1982; but see Balakrishnan and Ashby, 1991). One focus of current research is to establish the role of attentional control in small number processing. Challenging Trick and Pylyshyn's (1994) description of subitizing as being the outcome of mid-level visuo-spatial indexing processes operating prior to the allocation of focal attention, a number of recent studies failed to confirm the assumed independence from attentional modulation as a property of the instantaneous and precise enumeration capacity for small set sizes (Burr et al., 2010; Poiese et al., 2008; Railo et al., 2008; Vetter et al., 2011; but see Piazza et al., 2003). The results of these studies rather suggest that the distinction of stimulus-driven versus goal-oriented attentional functions as elaborated in Corbetta and Shulman's (2002) model may better describe the existing data (Ansari et al., 2007). A second strand of research is not so much concerned with capacity limited cognitive resources, but with the nature of representational systems mediating quantity processing for small and large arrays of objects (Feigenson et al., 2004). In a recent review, Piazza (2010) distinguishes two functionally and neuroanatomically dissociable systems fundamental for quantification processes. Whereas a substantial body of research corroborates models that link estimation of large numerical quantities to the functioning of an analog magnitude processing system located in inferior parietal regions of both hemispheres (see Dehaene, 2009, for a recent review), much less is known of a putative second system underlying the rapid and accurate processing of small collections of items. This latter, the so-called object tracking system (Feigenson et al., 2002), is assumed to be crucial for establishing and tracing individual tokens of objects (see Carey, 2009, Chapter 3) and to be linked to the functioning of extra-striate visual areas (Sathian et al., 1999; but see Izard et al., 2008). The assumption of a functional separation of representation systems for small and precise versus large and approximate quantities was recently supported by Palomares et al. (2011), who showed processing of the object tracking systems to be restricted to small numerosities, while the parietal processing system was demonstrated to be involved in stimulus processing across the whole numerical range.

Apart from experimental demonstrations of the behavioral manifestations of numerical distance effect in adults (Dehaene et al., 1990) and children (Sekuler and Mierkiewicz, 1977), neuroimaging methods such as electroencephalography (EEG); (Dehaene, 1996; Temple and Posner, 1998) and functional magnetic resonance imaging (fMRI); (Pinel et al., 2001, 2004) were used to explore its neural basis. And just recently, eye movement measures were used to tap into levels of numerical processing related to the execution of magnitude comparisons (Merkley and Ansari, 2010).

In their seminal paper on atypical number development, Ansari and Karmiloff-Smith (2002) suggested that differences in behavioral and neural manifestations of numerical distance effects may serve as predictors of individual mathematical competencies and may allow for specific insights into the relationship between impairments of basic numerical functions and the development of so-called end-state representational systems. Consequently, a number of studies have addressed developmental changes of manifestations of the numerical distance effect. It was demonstrated that the impact of distance manipulations on behavioral measures generally *decreases* in the course of development (Duncan and McFarland, 1980; Holloway and Ansari, 2008; but see Reynvoet et al., 2009). Interestingly, on the level of neural