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Research Report

Cortical activation patterns during subitizing and counting

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ABSTRACT

The exact amount of small number of items (1–4) can be detected fast and accurately (subitizing) while the enumeration of large number of items (over 4) is slower and error-prone (counting). Several counting-related cortical areas have been identified mainly in frontal and parietal regions, but cortical events associated with subitizing have remained unclear. Similarly, little is known about the temporal sequence of cortical activation during enumeration. In this study, we examined the temporal and spatial pattern of subitizing and counting using magnetoencephalography (MEG). During the MEG-recordings, black dots (2–8) in a visual display were shown to ten adults, who then responded with a button press as soon as they knew the number of items. The behavioural results showed a regularly reported dichotomy in enumeration of small (2–4) and large (5–8) numbers. In brain responses, pronounced activation peak during subitizing was detected around 250 ms in the bilateral posterior temporo-parietal area, which presumably reflects the function of ventral visual stream. During counting, pronounced activation was first detected in bilateral parietal areas, followed by a growing activation in the frontal cortices. The activation of frontal areas indicates the involvement of task guidance and attention, while the parietal areas activated earlier may have a key role in maintaining numerical representations and spatial attention. Brain functions during counting seem to consist of several constituent processes that reflect number processing, attention and task guidance. Our results demonstrated temporally and spatially specific brain activation for fast subitizing and effortful counting.

1. Introduction

The development of mathematical abilities begins soon after birth. Even babies can discriminate objects based on their number (Starkey and Cooper, 1980; Xu and Spelke, 2000). A toddler can already count a small number of items and slowly starts to familiarise with number words. These abilities enable the child to count increasingly larger arrays. Enumeration is the basis for comprehending the concept of number, and number perception can be regarded as a fundamental skill that enable children to acquire more complex mathematics at school.

Interestingly, the enumeration of small and large arrays seems to be dissimilar. In babies, the accuracy of discriminating numbers decreases when the number of the items increases: babies can discriminate between two and three item arrays but not between four and six item arrays (Starkey and Cooper, 1980) or eight and twelve item arrays (Xu and

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Spelke, 2000). Both children and adults can detect the exact amount of small number of items fast and accurately. The enumeration of small arrays (usually up to four items) can be accordingly described as a sudden feeling of knowing the amount of items without separately counting them. In order to know the exact number of a larger set of objects (five or more), some form of effortful counting must be applied instead (Piazza and Izard, 2009; Trick, 1992).

Behavioural studies further support the assumption that the enumeration might be qualitatively different for small and large numbers. When the participants are asked to report the number of visually shown items, only a minimal difference in response latencies is seen between one, two, three and four items. If five or more items are shown, the response latency increases linearly about 300 ms per every added item (Trick, 1992). A similar discontinuity has been noticed in the proportion of errors: enumeration of small number of items is highly accurate but from five items onwards, the proportion of errors increases. This discontinuity in response latency and accuracy has been suggested indicating that visual object enumeration is qualitatively different for small and large numbers. The fast and accurate way to enumerate small number of items is called subitizing (Kaufman et al., 1949). Subitizing is a parallel process, meaning that the number of the items is possible to enumerate at a glance. For larger sets, the number of items is enumerated serially one-by-one or in small groups. At the same time, the running total is held in mind and finally corresponded for example to a number word. This serial process is called counting. Subitizing range is usually from one to four items, and it varies between individuals and even within an individual as the items close to the subitizing limit can be either subitized or counted depending on the arrangement and the complexity of the stimuli (Alvarez and Cavanagh, 2004; Simons and Langheinrich, 1982).

Although the behavioural effect in small and large number enumeration has been widely investigated, the brain correlates of subitizing and counting are relatively poorly known. Metabolic changes in the brain during enumeration or a reference task have been compared in a few studies. Pronounced activation for subitizing in contrast with a reference task has been reported in temporo-parietal junction (TPJ) in the right hemisphere (subitizing vs. small number enumeration with high attentional load: Vetter et al., 2011), intraparietal sulcus in the right hemisphere (subitizing vs. seeing one object and saying "one": Piazza et al., 2002) and in the bilateral occipital cortex (Piazza et al., 2002; subitizing vs. single target detection: Sathian et al., 1999). The activation of rTPJ has been linked to the function of the ventral network of attention, that is, a stimulus-driven system that orients the attention toward unexpected and behaviourally relevant events (Ansari et al., 2007; Corbetta and Shulman, 2002; Vetter et al., 2011). The activation of the intraparietal sulcus has been suggested to reflect numerical processing (Piazza et al., 2002) and the function of the occipital areas during subitizing has been connected to early visual processing (Piazza et al., 2002; Sathian et al., 1999). On the other hand, some studies have failed to find any subitizing specific activation in comparison with either counting or a reference task (subitizing vs. colour naming: Piazza et al., 2003; subitizing vs. single target detection: Zago et al., 2010). Thus, the brain regions related to subitizing are still debatable.

Studies discussed above used positron emission tomography (PET) or functional magnetic resonance imaging (fMRI) to measure metabolic changes in the brain. As such techniques integrate activation over a relatively long time period, it is possible that fMRI is relatively insensitive to early, transient signals (Furey et al., 2006; Logothetis, 2008) associated with fast operations such as subitizing. In contrast, EEG and magnetoencephalography (MEG) measure the electromagnetic activity of the brain with excellent temporal resolution. Event-related potential (ERP) studies have reported most consistently effects related to subitizing approximately at 200–300 ms after the stimulus presentation during the negative deflections N2 or N2pc (Mazza and Caramazza, 2011; Nan et al., 2006; Pagano and Mazza, 2012). The N2pc component appears over the posterior areas of the brain, contralateral to the attended side, and has been proposed to reflect selective attention (Eimer, 1996). In an enumeration task, it seems that the amplitude of the N2pc component is modulated by the number of targets in the subitizing range (Mazza and Caramazza, 2011; Pagano and Mazza, 2012), but not in a target detection task with exactly the same stimuli (Mazza and Caramazza, 2011). ERP-signals during subitizing have also been compared with exact and approximate enumeration. When participants performed a parity judgement task, dissimilar signals for small (1–3) and large (4–6) numbers were detected appearing already at 200–400 ms after the stimulus presentation, although the dichotomy between small and large numbers did not appear in behavioural recordings (Nan et al., 2006). Instead, when contrasting subitizing and estimation, differences in ERP signals were not reported (Xu and Liu, 2008).

Several brain areas have been proposed to have an important role in counting (Piazza et al., 2003, 2002; Sathian et al., 1999; Zago et al., 2010). The activation of frontal and superior parietal areas has been consistently reported in brain imaging studies about counting and the activation of these areas has been associated with the shifting of the spatial attention (Piazza et al., 2003, 2002; Sathian et al., 1999; Zago et al., 2010). Serial shifts of attention seem to be essential in counting and indeed, counting fails if ocular movements are prevented (Oyama et al., 1981). Another consistent pattern of activation has been located to the bilateral intraparietal sulcus (IPS) (Piazza et al., 2003, 2002; Sathian et al., 1999; Zago et al., 2010). The horizontal segment of intraparietal sulcus (hIPS) in both hemispheres has shown reproducible activation in tasks requiring number manipulation (for a review see Dehaene et al., 2003). Thus, one explanation is that hIPS activation during counting reflects the mathematical component of counting. Finally, left-lateralized activation in premotor and temporal areas has been reported (Piazza et al., 2003, 2002; Zago et al., 2010). This activation has been suggested to reflect the verbal component of counting (subvocal articulation, verbal working memory). In fact, according to Piazza and Izard (2009), spatial shifts of attention and working memory are two crucial mechanisms required in counting. Still, the temporal course of the activation in different areas has remained unclear. To our knowledge, exact counting has not been investigated utilising temporally sensitive brain imaging techniques. In previous EEG-studies investigating large number perception, the participants have performed parity judgement