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Executive function effects and numerical development in children: Behavioural and ERP evidence from a numerical Stroop paradigm

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ABSTRACT

Most research on numerical development in children is behavioural, focusing on accuracy and response time in different problem formats. However, Temple and Posner (1998) used ERPs and the numerical distance task with 5-year-olds to show that the development of numerical representations is difficult to disentangle from the development of the executive components of response organization and execution. Here we use the numerical Stroop paradigm (NSP) and ERPs to study possible executive interference in numerical processing tasks in 6–8-year-old children. In the NSP, the numerical magnitude of the digits is task-relevant and the physical size of the digits is task-irrelevant. We show that younger children are highly susceptible to interference from irrelevant physical information such as digit size, but that access to the numerical representation is almost as fast in young children as in adults. We argue that the developmental trajectories for executive function and numerical processing may act together to determine numerical development in young children.

According to the most widely accepted theory of numerical cognition (Dehaene, 1997), the human brain represents numerical magnitudes in an analog manner. This analog magnitude representation is akin to the way we represent physical magnitudes, for instance size, luminance or line length. Several investigators have studied the putative electrophysiological markers of the analog magnitude representation in adults (Dehaene, 1996; Libertus, Woldorff, & Brannon, 2007; Pinel, Dehaene, Riviere, & LeBihan, 2001; Szucs & Csepe, 2004a,b, 2005a,b) and in adolescents/children (Soltész, Szucs, Dekany, Markus, & Csepe, 2007; Soltész, White, & Szucs, 2011; Szucs, Soltész, Jarmi, & Csepe, 2007; Temple & Posner, 1998). Some of these studies have demonstrated that the impact of developing executive functions has to be taken into account if we want to understand behavioural developmental effects in number cognition (Szucs, Soltész, Bryce, & Whitebread, 2009; Szucs et al., 2007; Temple & Posner, 1998). As demonstrated by Temple and Posner (1998), electro-encephalography (EEG) provides an optimal means to disentangle numerical and executive processes because of its high temporal resolution. In the current study, our objective was to disentangle executive and numerical processes in the developmental trajectory of numerical processing during the initial stages of primary school education.

The most important marker of basic numerical processes is the so-called numerical distance effect (NDE). According to the NDE, the larger the distance between two numbers, the easier it is to discriminate between them (Moyer & Landauer, 1967). In other words, it is more difficult to judge two magnitudes as different when they are close to each other (i.e. more similar to each other) than when they are further apart. An analogy is being at a party and trying to select the largest piece of birthday cake. If the host cuts the cake into pieces of obviously different magnitude, the choice is easy. However, if the cake has been cut precisely, so that the pieces are very similar to each other in size, it takes more time and effort to select the largest piece. In the same way, numerical magnitudes which are closer to each other (e.g. 3 and 4) are more difficult to discriminate than magnitudes which are further apart (e.g. 3 and 9).

The numerical distance effect is considered as a marker of the activation of the magnitude representation in the brain. Its existence has been shown consistently in number comparison or number discrimination tasks given to animals (e.g. Mechner, 1958; Platt & Johnson, 1971; Whalen, Gallistel, & Gelman, 1999; Gallistel & Gelman, 2000; Cantlon & Brannin, 2007), infants (Brannon, Abbot, & Lutz, 2004; Xu & Arriaga, 2007; Xu & Spelke, 2000), children (Rouselle & Noël, 2008; Sekuler & Mierkiewitz, 1977), and adults (for reviews see: Gallistel & Gelman, 2000; Feigenson, Dehaene, & Spelke, 2004; Dehaene, Molko, Cohen, & Wilson, 2004; Cantlon et al., 2008). The fact that the NDE is found across species and ages in number discrimination tasks suggests that we all share an evolutionary inherited, common representation of approximate numerical magnitudes. Neuroimaging studies suggest that the analog magnitude representation may reside in the horizontal intraparietal sulcus of the human brain (for an overview see Dehaene et al., 2004). The NDE has been demonstrated in blood-oxygen-level-

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dependent responses in functional magnetic resonance studies (Pinel et al., 2001; Pinel, Piazza, Le Bihan, & Dehaene, 2004; Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004; Piazza, Pinel, Le Bihan, & Dehaene, 2007; Kaufmann et al., 2005) and also in stimulus-related electrical activity measured by electro-encephalography (event-related potentials: ERPs). In ERPs, the distance effect has been demonstrated in adults (for example: Grune, Mecklinger, & Ullsperger, 1993; Dehaene, 1996; Szucs & Csepe, 2004a,b, 2005a,b) and in children (Szucs et al., 2007; Temple & Posner, 1998). ERP signatures of the NDE have also been shown in adolescents with developmental dyscalculia (Soltész et al., 2007), suggesting broad similarity of magnitude processing in the brain across ages and populations.

ERP measurement has the advantage of high temporal resolution (in the range of milliseconds). This means that it can capture neural signatures of cognitive processes long before the overt responses are made. For example, Temple and Posner (1998) asked adult and 5-year-old participants to decide whether a number presented visually was smaller or larger than five. The magnitude judgement was made by pressing a button. When the target number was smaller than 5, the response required one button, and when the target number was larger than 5, the response required another button. Temple and Posner reported a considerable difference in the speed of the response (pressing the button) between children and adults: children were more than 3 times slower, lagging behind adults by approximately 1 s (480 ms response time in adults and 1495 ms response time in children). Surprisingly, there was no such difference in the numerical distance effect, which was measured by ERPs. Both children and adults showed the ERP distance effect at around 200 ms after stimulus presentation. The ERPs hence indicated that numerical processing was as fast in children as in adults. Temple and Posner suggested that the delayed magnitude judgements in children were due to less well-developed inhibitory and response organization abilities. Access to numerical representations per se appeared to be as fast in children as in adults. Temple and Posner's (1998) data suggest that the co-development of executive functioning and numerical skills has to be disentangled in research on numerical development. The important implication of their findings is that the most important developmental changes affecting behavioural outcomes in simple number comparison tasks may occur at the level of executive functioning rather than at the level of number processing skills. By corollary, developmental difficulties in executive functioning may play a previously unsuspected role in developmental dyscalculia (Soltész & Szucs, 2009; Soltész et al., 2007).

One way of disentangling executive and numerical processes is to use the numerical Stroop paradigm (Szucs et al., 2007; see later). In the numerical Stroop paradigm (NSP), it is possible to test simultaneously number processing skills, the organization of responses and the inhibition of irrelevant information. This makes the NSP an excellent paradigm for investigating whether separate developmental trajectories for executive vs. number skills play a role in numerical development. As in the classic color–word Stroop paradigm (Stroop, 1935), the numerical Stroop paradigm varies the perceptual features of the stimuli so that their conceptual meaning is either *facilitated* or *interfered* with. In the color–word Stroop, when the meaning of the word is in agreement with the ink color of the word (e.g. the word 'red' written with red ink), participants show facilitation in naming the ink color of the written words. This is the *congruent* condition. When the meaning of the word is in conflict with the ink color of the word (e.g. the word 'red' written with green ink), participants show inhibition in naming the ink color of the written words, responding more slowly and making more errors. This is the *incongruent* condition. Similarly, the task-relevant and the task-irrelevant dimensions can be congruent or incongruent with each other in a numerical comparison task.

With the initial version of this paradigm (Besner & Coltheart, 1979), one can examine whether physical size interferes with numerical magnitude, or not. When first applied, the numerical Stroop paradigm was theoretically the opposite of the original Stroop paradigm: participants were asked to decide upon the numerical size (the meaning of the symbol) and to ignore the physical size (the physical attribute of the symbol). In fact, physical size interferes with the numerical magnitude: participants slow down and commit more errors, when the physical dimension of the stimuli is incongruent with the numerical meaning.In the NSP the numerical and the physical magnitudes of digits are varied in an orthogonal fashion. If the numerically larger number is larger in physical size as well, this constitutes the congruent condition. If the numerically larger number is smaller in physical size, this constitutes the incongruent condition (see Fig. 1). *Facilitation* is the gain in accuracy and in response time in the congruent condition and *interference* is the cost in accuracy and in response time in the incongruent condition. When adult participants are asked to compare numerical magnitudes and ignore the physical dimension of the stimuli, usually both facilitation and interference effects are found (Besner & Coltheart, 1979; Henik & Tzelgov, 1982; Tzelgov, Meyer, & Henik, 1992). These findings suggest that the representations of, and/or the decisional processes on, numerical and physical magnitudes are overlapping with each other. The Stroop effects show that physical features are *automatically* processed, even when they are irrelevant to the task. Posner (1978) described automaticity as a process which is similar to reflexive behaviour, in that it runs without intention, attention or awareness. Although the role of attention is debated (e.g. Carr, 1992), it is agreed upon that an automatic process does not need monitoring to be executed (Logan, 1980; Zbrodoff & Logan, 1986). So that, if the non-monitored (task-irrelevant) features of the stimuli influence task performance and an interaction of the relevant and irrelevant features emerge, one can conclude that the irrelevant features are auotmatically processed. The interaction of numerical and physical magnitudes has been called the *size congruity effect* (Besner & Coltheart, 1979). This size congruity effect serves as an indicator of cognitive conflict and can be used as a measure of automatic processing and inhibition. More precisely, both facilitation and interference indicate the automatic processing of a certain feature (Logan, 1980), while interference reflects the inability to inhibit irrelevant and conflicting information as well (Posner, 1978; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002). In the case of an incongruent stimulus, it is one's best interest to inhibit irrelevant information, in order to avoid the conflict during problem solving or task execution. If interference is present, it reflects that the inhibition of irrelevant information was not fully successful.

Two behavioural studies have been undertaken to explore the size congruity effect in children. Girelli, Lucangeli, and Butterworth (2000) tested 1st, 3rd and 5th graders and adults in the NSP. In the numerical task, where subjects had to pick the numerically larger digit, Girelli et al. reported significant size congruity effects for all age groups. More precisely, facilitation was significant and did not change across age, while there was a developmental pattern for interference. Interference effect was significant in accuracy in all grades, but it emerged only in 3rd grade in RTs, suggesting that younger children were less sensitive to interference than their older peers. Girelli et al. argued that the effect of incongruity was determined by the level of integration between the two dimensions: the association between numerical symbols and their meanings develops gradually in the course of learning. Physical size was processed automatically and

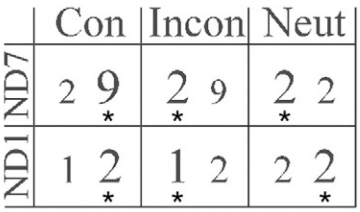

Fig. 1. Example stimuli demonstrating the levels of numerical distance (ND 1 and ND 7) and the levels of congruency.