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Event-related potentials dissociate facilitation and interference effects in the numerical Stroop paradigm

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Abstract

In the numerical Stroop paradigm (NSP) participants compare simultaneously presented Arabic digits based on either their numerical or on their physical size dimension. Responses are faster when the numerical and size dimensions are congruent with each other (facilitation), and responses are slower when the numerical and size dimensions are incongruent with each other (interference). We aimed to find out whether facilitation and interference appears during the course of perceptual or response processing. To this end, facilitation and interference effects in the amplitude of event-related brain potentials (ERPs) were examined. The onset of motor preparation was determined by monitoring the lateralized readiness potential. In numerical comparison one facilitation effect was related to perceptual processing at the level of the magnitude representation. A second facilitation effect and interference effects appeared during response processing. In size comparison facilitation and interference appeared exclusively during response processing. In both tasks, ERP interference effects were probably related to contextual analysis and to the conflict monitoring and selection for action activity of the anterior cingulate cortex. The results demonstrate that facilitation and interference effects in the NSP appear during multiple stages of processing, and that they are related to different cognitive processes. Therefore these effects should be clearly separated in studies of the NSP. A model of the processes involved in the NSP is provided and implications for studies of the NSP are drawn.

Keywords: Numerical cognition; Stroop effect; Parietal magnitude representation; Distance effect; Perceptual and response processing; Anterior cingulate cortex; N400; P3b; LPC

1. Introduction

In the so-called numerical Stroop paradigm (NSP) participants compare simultaneously presented Arabic digits based on either their physical or on their numerical dimension (Besner & Colthart, 1979; Henik & Tzelgov, 1982). The outcome of numerical and physical size comparison can be congruent or incongruent with each other (see Fig. 1). Congruence of the task-relevant and task-irrelevant stimulus dimensions affects reaction times (RTs): RTs may be faster in the congruent than in the neutral condition (this is called facilitation), and RTs are usually slower in the incongruent than in the neutral condition (this is called interference). The phenomena of facilitation and interference suggest that task-irrelevant stimulus dimensions are processed. This is especially interesting in the physical comparison task of the NSP, where the presence of facilitation and/or interference suggests that the irrelevant numerical dimension of the stimuli has been processed. Hence, recently the NSP has been widely used to measure whether there is automatic access to numerical magnitude information in both adults (Girelli, Lucangeli, & Butterworth, 2000; Henik & Tzelgov, 1982; Kaufmann et al., 2005; Pinel, Piazza, Le Bihan, & Dehaene, 2004; Rubinstein & Henik, 2005; Rubinstein, Henik, Berger, & Shahar-Shalev, 2002) and children (Girelli et al., 2000; Rubinstein et al., 2002; Kaufmann et al., 2006). However, despite the popularity of this paradigm, to date there is no clear account of the cognitive component processes involved in the NSP. Here, relying on the excellent temporal resolution of electro-encephalography, we present a study of facilitation and interference processes. We conclude by a detailed account of the processes involved in the NSP and highlighting the implications of the results.

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	Neutral	Congruent	InCongruent
Numerical Task	2 7	2 7	2 7
Size Task	2 2	2 7	2 7
Effect		Facilitation	Interference

Fig. 1. Examples of stimulus pairs used in the experiment. In the numerical comparison task subjects decide which digit represents a numerically larger number. In the physical comparison task subjects decide which digit is larger in physical size. In the congruent condition a digit is larger/smaller than the other one in both numerical magnitude and physical size. In the incongruent condition a digit is larger (smaller) than the other one in numerical magnitude but smaller (larger) than the other one in physical size. The correct response in both tasks in each condition is underlined. Expected effects are denoted in the row "effect".

In the classical colour-word Stroop paradigm (Stroop, 1935) there is interference when the subject has to name the colour of the ink (i.e. irrelevant word-meaning interferes with naming colours), but not when the subject has to read colour-words (i.e. irrelevant colour does not interfere with word-meaning). In contrast, in the NSP congruency effects between numerical and physical magnitude information are typically bidirectional (Girelli et al., 2000; Henik & Tzelgov, 1982; Kaufmann et al., 2005; Pansky & Algom, 1999; Pinel et al., 2004; Rubinstein & Henik, 2005; Rubinstein et al., 2002; Schwarz & Heinze, 1998; Tzelgov, Meyer, & Henik, 1992). This suggests that the numerical and physical stimulus dimensions are processed in parallel, that their processing time is highly overlapping, and that the two dimensions receive a similar amount of involuntary attention[1] (Henik & Tzelgov, 1982; LaBerge & Samuels, 1974; MacLeod, 1991). Drawing on the literature of the colour-word Stroop effect (for a review see MacLeod, 1991), congruency effects in the NSP can be explained by interactions appearing during perceptual and/or response processing.

According to the perceptual interaction view, the representations of task-relevant and task-irrelevant stimulus dimensions are constructed in parallel, and they interact at the level of stimulus perception (Hock & Egeth, 1970). Facilitation appears when compatible stimulus representations enhance each others' perceptual processing. Interference is a consequence of resolving the incompatibility between conflicting stimulus representations. Hypothetically, in the NSP task-relevant and task-irrelevant stimulus representations can interact with each other at the perceptual level in two ways (Schwarz & Heinze, 1998). One possibility is that numerical meaning and physical size are processed by different neural networks, independently from each other, interacting only through associative links. Another possibility is that numerical meaning and physical size are processed by a common neural representation.

Current numerical cognition research seems to support the second, common representational view of perceptual interaction. Several imaging studies suggest that there is a common representation of both physical and numerical magnitude in the bilateral horizontal intraparietal sulci (for a review see Dehaene, Molko, Cohen, & Wilson, 2004). In these brain areas functional magnetic resonance imaging (fMRI) studies have found modulations of brain activity as a function of numerical distance between the to-be-compared symbolically denoted numbers (Pinel, Dehaene, Riviere, & LeBihan, 2001, 2004; Kaufmann et al., 2005), non-symbolically denoted quantities (e.g. dot patterns; Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004) and as a function of physical distance between to-be-compared physical quantities (e.g. line angles; Fias, Lammertyn, Reynvoet, Dupont, & Orban, 2003). In an fMRI study Pinel et al. (2004) asked subjects to compare pairs of Arabic digits, focusing on their numerical magnitude, physical size, or luminance. The numerical distance between digits and difference in the physical size of digits were manipulated. The analysis of the distance effects revealed that partially overlapping brain areas, predominantly in the right horizontal intraparietal sulci, were sensitive to the manipulation of both numerical and physical distance. The results converge with behavioural observations (Fias, Lauwereyns, & Lammertyn, 2001; Lammertyn, Fias, & Lauwereyns, 2002), and strongly support the idea that the representations of numerical and physical magnitude are subserved by overlapping networks in the human brain. This evidence suggests that numerical magnitude and physical size information may interact with each other in this common magnitude representation form.

An alternative to the perceptual interaction view is the relative speed of processing, or horse-race model (Morton & Chambers, 1973; Posner & Snyder, 1975). This model assumes that parallel processed stimulus dimensions are competing to dominate response activity. Interference does not occur during stimulus perception, but rather, it happens as a result of response-competition between the motor responses to the task-relevant and task-irrelevant stimulus dimensions. Electromyographic evidence suggests that task-irrelevant information can activate the muscles of the incorrect response hand, even if no incorrect response happens (Coles, Gratton, Bashore, Eriksen, & Donchin, 1985; Eriksen, Coles, Morris, & O'Hara, 1985; Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988). This suggests that perceptual and response processes does not follow each other in a serial fashion (Sternberg, 1969). Rather, in line with the assumption of the "continuous flow model" (Eriksen & Schultz, 1979), as soon as an adequate amount of perceptual information becomes available, perceptual processes begin to bias response activity in a continuous fashion before the final completion of stimulus analysis. An overt response is produced when the activation of a possible response exceeds a criterion (Eriksen & Schultz, 1979; Smid, Mulder, & Mulder, 1990). A response-level interaction between task-relevant and task-irrelevant stimulus features occurs during motor preparation.

In principle, the excellent temporal resolution of event-related brain potentials (ERPs) provides a means to determine

[1] The differential attentional allocation view of the colour-word Stroop effect presumes that interference arises because processing one aspect of the stimulus requires considerably more attention than processing the other aspect, which is processed in an obligatory fashion: The more automatically processed attribute causes interference in the processing of the less automatically processed attribute, but not vice versa (LaBerge and Samuels, 1974; Posner and Snyder, 1975). This explanation of interference cannot be applied to the NSP, as both numerical and physical information seems to benefit from a similar amount of involuntary attention.