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Separating stages of arithmetic verification: An ERP study with a novel paradigm

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ABSTRACT

In studies of arithmetic verification, participants typically encounter two operands and they carry out an operation on these (e.g. adding them). Operands are followed by a proposed answer and participants decide whether this answer is correct or incorrect. However, interpretation of results is difficult because multiple parallel, temporally overlapping numerical and non-numerical processes of the human brain may contribute to task execution. In order to overcome this problem here we used a novel paradigm specifically designed to tease apart the overlapping cognitive processes active during arithmetic verification. Specifically, we aimed to separate effects related to detection of arithmetic correctness, detection of the violation of strategic expectations, detection of physical stimulus properties mismatch and numerical magnitude comparison (numerical distance effects). Arithmetic correctness, physical stimulus properties and magnitude information were not task-relevant properties of the stimuli. We distinguished between a series of temporally highly overlapping cognitive processes which in turn elicited overlapping ERP effects with distinct scalp topographies. We suggest that arithmetic verification relies on two major temporal phases which include parallel running processes. Our paradigm offers a new method for investigating specific arithmetic verification processes in detail.

1. Introduction

Arithmetic verification paradigms have been extensively used in event-related brain potential (ERP) research on mathematical cognition (Avancini et al., 2014; Galfano et al., 2004; Galfano et al., 2009; Jasinski and Coch, 2012; Jost et al., 2004; Núñez-Peña, 2008; Núñez-Peña et al., 2011; Szűcs and Csépe, 2004, 2005; Szűcs and Soltész, 2010). In these paradigms participants typically encounter two operands shown simultaneously or in succession and they carry out an operation (e.g. adding them). Operands are followed by a proposed answer (sometimes called a probe) and participants decide whether this answer is correct or incorrect. Typically, verification tasks use addition and multiplication operations, mostly with single digit numbers (Chen et al., 2013; Domahs et al., 2007; Galfano et al., 2011; Núñez-Peña et al., 2004; Prieto-Corona and Rodríguez-Camacho et al., 2010; Szűcs and Csépe, 2005; Zhou et al., 2006) and rarely with two-digit numbers (El Yagoubi et al., 2005). Verification tasks provide insights into the organization of arithmetic facts (Galfano et al., 2009), arithmetic solution strategies (Jasinski and Coch, 2012), magnitude discrimination processes (Jost et al., 2004; Szűcs and Csépe, 2005) and arithmetic memory (Szűcs and Csépe, 2004). While arithmetic verification tasks are deceptively straightforward, they require the engagement of various simultaneous cognitive processes in order to be carried out successfully. Consequently, the interpretation of ERP results is not necessarily simple, as brain potentials are affected by several temporally overlapping processes. Here we introduce a new paradigm to dissociate relevant cognitive processes. This paradigm allows us to clearly dissociate the cognitive components of verification tasks.

When in a verification task the two operands are presented first, they are thought to automatically activate the correct answer stored in a network-like organized memory, with mechanisms similar to those assumed to operate in the linguistic domain (Ashcraft, 1992; Collins and Loftus, 1975; Domahs and Delazer, 2005; Galfano et al. 2003). When an incorrect response is shown, it violates the semantic constraints defined by the operands, similarly to linguistic semantic incongruities. The main ERP evidence for the involvement of semantic processes comes from the elicitation of the N400 and the P3b components. The N400 effect is a negative wave with about 400 ms latency and it is thought to be a correlate of the processing of semantic information stored in a cerebral network accessible from multiple input formats and it has been typically detected in evaluation of semantically anomalous

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words in sentence contexts (see Kutas and Federmeier, 2000; 2011). The N400 effect appears in response to arithmetic incongruence and it is often thought to reflect semantic arithmetic judgments (Galfano et al., 2004; Galfano et al., 2009; Niedeggen and Rösler, 1999; Niedeggen et al., 1999; Szűcs and Soltész, 2010). The P3b is usually considered to be an index of contextual integration related to the process of stimulus categorization (Donchin, 1981) and subsequent memory updating and storage (Polich, 2007). In verification tasks incorrect proposed results elicit increased P3b amplitude (Niedeggen et al., 1999; Jasinski and Coch, 2012). This effect usually peaks between 500 and 600 ms after stimulus onset and may be delayed after incorrect proposed results compared to correct proposed results (Szűcs and Csépe, 2004, 2005).

A second process playing a role in arithmetic verification tasks is the potential violation of strategic expectations within a certain task context. When judging the arithmetic correctness of the proposed answers, participants detect whether the proposed results match or do not match their expectations about being correct or incorrect. Such detection of violation of strategic expectations is independent from the mathematical 'correctness' of proposed results and usually depends on the proportion of correct/incorrect results (Szűcs and Csépe, 2005; Hsu and Szűcs, 2011). For example, if most proposed results are incorrect, a priori participants may expect incorrect rather than correct results. Hence, if they encounter correct rather than incorrect results their strategic expectations are violated. Strategic and semantic expectations may dissociate. For example, Szűcs and Csépe (2005) showed that modifying stimulus probabilities in arithmetic tasks affects strategic expectations of correct/incorrect probes. Such strategic expectations modulate the amplitude of the P3b ERP wave which is sensitive to subjective expectations about stimulus probability (Donchin, 1981; Polich, 2007). Such modulations can then be confused with arithmetic specific effects as shown by Szűcs and Csépe (2005) and Szűcs and Soltész (2010). Hsu and Szűcs (2011) have also shown that presenting semantically non-matching stimuli more frequently than matching stimuli affects task solution strategies by prompting participants to expect the more frequent (but arithmetically non-matching). They observed that a negativity peaking at about 200 ms after stimulus presentation (called Arithmetic Mismatch Negativity) is a correlate of strategic expectations and it is modulated by the manipulation of correct/incorrect response ratio.

Another process to consider in verification tasks is the detection of mismatch in visual stimulus properties. Related ERP effects have been reported in response to a wide range of stimulus attributes like category, format, shape and magnitude (Cui et al., 2000; Szűcs et al., 2007). ERP effects appear when the second stimulus of a pair does not match the previous stimulus of the pair in some characteristics. The detection of stimulus mismatch is likely to be the outcome of general conflict detection/processing (Wang et al., 2001). In ERP studies, visually non-matching stimuli elicit an enhanced N2b component (Wang et al., 2001). Szűcs et al. (2007) found this N2b to be more negative in a colour-mismatch condition than in a colour-match condition at fronto-central sites, thus supporting the idea that the N2b is a general correlate of detecting mismatch between representations of task-relevant features and that it is functionally dissociated from the N400. Furthermore, the late part of the P3b (between 450 and 550 ms) is also elicited by physically mismatching stimuli, being more positive to colour mismatch when this mismatch was task-relevant (Szűcs et al., 2007).

Finally, numerical magnitude comparison processes are also involved in arithmetic verification task performance. These are activated when participants make voluntary or involuntary comparisons between the proposed result and the result retrieved from memory. Such operations elicit the so-called *numerical distance effect,* which was first observed in number comparison tasks (Pinel et al., 2001). Electrophysiological studies detected the ERP correlates of this distance effect between 140 and 500 ms (Szűcs and Csépe, 2005; Szűcs and Soltész, 2007, 2010; Szűcs et al., 2007b). The topography of the effect is fairly diffuse until around 250 ms and is usually parieto–occipital after 300 ms (Szűcs and Soltész, 2008). Although some data report the distance effect only over the right hemisphere (Szűcs and Csépe, 2004, 2005b) and other data detect it over both hemispheres (Soltész et al., 2007), it does seem to be most clearly expressed over the right scalp (Szűcs et al., 2007b).Variations in topographies might be due to the fact that an extended network of brain areas takes part in even simple numerical comparison (Szűcs et al., 2007b). Once more, the components involved are the N2b and the P3b. Specifically, the larger the deviation of errors from the correct result, the more negative the N2b amplitude and the shorter its latency, while the increase of numerical distance resulted in more positive P3b, suggesting that the larger the deviation of errors from the correct result, the more activated are cognitive processes related to mismatch detection (El Yagoubi et al., 2003; Niedeggen and Rösler, 1999; Núñez-Peña and Honrubia-Serrano, 2004, Szűcs and Csépe, 2005).

In light of our review it appears that multiple parallel, temporally overlapping and strongly correlated numerical and non-numerical processes contribute to task execution. Investigating arithmetic problem solving by means of a typical arithmetic verification paradigm confounds all the above processes, preventing one from drawing clear conclusions on the temporal structure of the cognitive events involved in arithmetic verification decision. An important factor is that numerical magnitude comparison can be affected by task-relevant non-numerical discrimination processes rather than by number specific representational effects (Van Opstal and Verguts, 2011; Wong and Szűcs, 2013). Therefore, the task relevancy of correctness judgements in verification tasks introduces a major confound. A further complication is that previous studies mainly used a proportion of 50% of incorrect probes (Jasinski and Coch, 2012; Niedeggen and Rösler, 1999; Niedeggen and Rösler, 1999; Núñez-Peña, 2008; Núñez-Peña and Honrubia-Serrano, 2004; Núñez-Peña et al., 2004; 2011; Szűcs and Csépe, 2004). This is not optimal as participants build up strong subjective expectation of correct answers which strongly influences ERP data (Szűcs and Csépe, 2005 exp. 2; Szűcs and Soltész, 2010).

In order to cope with the problems described above, we analysed the ERP effects elicited by a novel verification paradigm specifically designed to tease apart the overlapping cognitive processes/factors active during arithmetic verification. To this end, arithmetic correctness and task-relevant stimulus decisions were manipulated independently of each other. This was made possible by designing a task where participants were not required to make any judgments about the arithmetic correctness of additions but instead they decided whether the parity of the sum of operands was the same as that of a third number. In addition, physical stimulus features were also manipulated orthogonally to the above two factors. This was achieved by presenting most stimuli in black font and 10% of stimuli in red font. According to the classical study of Kutas and Hillyard (1980) stimuli in red font should elicit ERP waves related to their physically unexpected nature. Taken together, the above properties of our paradigm allowed for the clear separation (through orthogonal manipulation) of ERP effects related to the cognitive processes of arithmetic correctness, violation of strategic expectations and physical stimulus properties mismatch. Moreover, our novel paradigm also allowed for the study of numerical distance effects without the confounding effect of making task-relevant numerical discrimination decisions. This was possible because participants were not required to make any overt arithmetic correctness judgments; they only carried out parity