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Sequential modulations of poorer-strategy effects during strategy execution: An event-related potential study in arithmetic

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ABSTRACT

When participants accomplish cognitive tasks, they obtain poorer performance if asked to execute a poorer strategy than a better strategy on a given problem. These poorer-strategy effects are smaller following execution of a poorer strategy relative to following a better strategy. To investigate ERP correlates of sequential modulations of poorer-strategy effects, we asked participants ($n = 20$) to accomplish a computational estimation task (i.e., provide approximate products to two-digit multiplication problems like 38×74). For each problem, they were cued to execute a better versus a poorer strategy. We found event-related potentials signatures of sequential modulations of poorer-strategy effects in two crucial windows (i.e., between 200 and 550 ms and between 850 and 1250 ms) associated with executive control mechanisms and allowing conflict monitoring between the better and the cued strategy. These results have important implications on theories of strategies as they suggest that sequential modulations of poorer-strategy effects involve earlier as well as later mechanisms of cognitive control during strategy execution.

1. Introduction

During the last three decades, many studies have shown that individuals use various strategies to accomplish most cognitive tasks (Siegler, 2007). A strategy can be defined as “a procedure or a set of procedures for achieving a higher level goal or task” (Lemaire & Reder, 1999, p. 365). One central issue concerns how participants execute a selected strategy on each item. Previous empirical research has found that factors characterizing participants, strategies, and situations crucially influence strategy performance on a given trial. Several computational and non-computational models of strategies have formalized strategy selection and execution processes (e.g., Lovett & Anderson’s, 1996 ACT-R model, Lovett & Schunn’s, 1999 RCCL model, Payne et al’s., 1993 Adaptive Decision Maker model, Rieskamp & Otto’s, 2006 SSL model, or Siegler & Arraya’s, 2005 SCADS* model). Although these models differ in some details, they share core assumptions regarding how participants execute strategies on each problem. For example, all models proposed that participants execute strategies on a problem-by-problem basis without necessarily being influenced by the strategy that has been executed on the preceding trial. Models also assume that the number and difficulty of procedures within each strategy determine strategy performance, with strategies including fewer and/or easier processes yielding better performance than strategies including more and/or harder processes.

Recent empirical findings of sequential effects have challenged several assumptions made by theories of strategies. Previous research found that the strategy executed on the previous problem influences strategy performance on the current problem (Lemaire & Lecacheur, 2010; Luwel, Schillemans, Onghena, & Verschaffel, 2009; Uittenhove, Poletti, Dufau, & Lemaire, 2013), falsifying the assumption of sequential independence of strategy execution. For example, Lemaire and Hinault (2013) asked participants to accomplish a computational estimation task (e.g., finding an approximate product to two-digit multiplication problems such as 43×68) with either of two rounding strategies: mixed-rounding up–down (i.e., rounding the first operand up to the nearest decade and the second operand down to the nearest decade, for instance doing 50×60 to estimate 43×68) and mixed-rounding down–up (i.e., rounding the first operand down to the nearest decade and the second operand up to the nearest decade, for instance doing 40×70 to estimate 43×68). They distinguished better-strategy problems when the cued strategy was a better strategy and poorer-strategy problems when the cued strategy was a poorer strategy. Poorer and better strategy were distinguished based on how close

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estimates yielded by each strategy are from current products. For example, mixed-rounding down–up such as doing 40 × 70 is a better strategy on 43 × 68 whereas mixed-rounding up–down such as doing 50 × 60 is a better strategy on 48 × 62. Participants' performance revealed poorer-strategy effects (i.e., slower performance with poorer relative to better strategy). Poorer-strategy effects can be accounted for by assuming that, when participants are asked to execute a poorer strategy on a given problem, they need to overcome tendency to use a better, most easily available (sometimes automatically activated) strategy. They do not have to do this when executing a better strategy. More importantly, poorer-strategy effects on current problems decrease after executing a poorer strategy on the preceding problem compared to after using a better strategy.

Lemaire and Hinault (2013) proposed that sequential modulations of poorer-strategy effects are due, at least in part, to control mechanisms resolving conflict between automatically activated strategy and required strategy that differ on poorer-strategy problems. Following theories of cognitive control (Botvinick, Braver, Barch, Carter, & Cohen, 2001; De Pisapia & Braver, 2006. See Mayr & Awh, 2009, and Scherbaum, Dshemuchadse, Ruge, & Goschke, 2012, for alternative views), the cognitive control system detects a conflict on non-congruent items, this in turn would lead the cognitive system to increase its level of control to inhibit the irrelevant (or less easily available) dimension and respond to the relevant dimension. This adaptation will lead to a more efficient conflict resolution on the next problems. Sequential modulations of poorer-strategy effects are important for theories of strategies, as they suggest that cognitive control mechanisms may be necessary to inhibit the most activated yet irrelevant strategy. Current models of strategies do not assume that participants need to use cognitive control processes to select or execute strategies. Neither do they assume modulations of these control processes across trials during strategy execution. Moreover, sequential modulations of poorer-strategy effects extend effects previously found in the general executive control literature (e.g., Gratton, Coles, & Donchin, 1992; Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002) to the case of more complex cognitive tasks consisting of multiple stimuli, responses, and strategies.

Previous event-related potential studies of strategies revealed that retrieval involved mainly left hemisphere of the brain (e.g., Herron & Rugg, 2003) while others strategies (e.g., counting, transforming the problem into smaller sub-problems) involved a parietal–occipital network (e.g., Grabner & De Smedt, 2011). Regarding strategy selection, El Yagoubi, Lemaire, and Besson (2003) found that the choice between exhaustive-calculation and approximate-calculation strategies occurred 250 ms after stimulus presentation. In a study of sequential modulations of strategy execution during two-digit multiplication problem solving, Uittenhove et al. (2013) found larger cerebral activities when the strategy on a given problem followed execution of a more difficult strategy (i.e., in a multiplication problem, rounding both operands up to the nearest decade) compared to an easier strategy (i.e., rounding both operands down to the nearest decade), in anterior left region of the brain. These sequential modulations occurred between 200 and 550 ms, a time window during which participants encode problems, as shown by previous research in arithmetic (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999).

In arithmetic processing, previous works (Dehaene et al., 1999; Iguchi & Hashimoto, 2000; Pauli et al., 1994; Stanescu-Cosson et al., 2000) demonstrated a larger contribution of left hemisphere of the brain, consistent with language involvement in mental calculation. Arithmetic fact retrieval also involves posterior areas of the brain, which is in accordance with studies indicating parietal cortex involvement in memory retrieval (e.g., Vilberg & Rugg, 2008). Moreover, arithmetic processing is associated with late positive complex, peaking between 500 and 1000 ms (Galfano, Mazza, Angrilli, & Umiltà, 2004; Kiefer & Dehaene, 1997).

Also, relevant to the present project, previous research on cognitive control (Clayson & Larson, 2011a,b; Forster, Carter, Cohen, & Cho, 2011; Larson, Clayson, & Baldwin, 2012; Larson, South, Clayson, & Clawson, 2012) demonstrated that the N2 component (i.e., fronto-central negative deflection peaking around 250–350-ms post-stimulus presentation) and the P3 component (i.e., centro-parietal positive deflection peaking between 350 and 500 ms post-stimulus presentation) are associated with high level of response conflict and conflict adaptation effects in a Flanker task. According to these studies, N2 is sensitive to the degree of response conflict while P3 is associated with response inhibition. Other studies in Stroop tasks (Larson, Kaufman, & Perlstein, 2009; Tang, Hu, Li, Zhang, & Chen, 2013) found that N450 (i.e., fronto-central negative deflection elicited about 400–550-ms following stimulus presentation) and conflict SP (i.e., sustained positivity starting about 500 ms following stimulus presentation) components were associated with cognitive control. Recent research (Larson et al., 2009; West, Bowry, & McConville, 2004; West, Jakubek, Wymbs, Perry, & Moore, 2005) indicated that N450 indexes conflict detection on the current trial while SP is associated to the increased implementation of attentional control. However, contrary to N2 and conflict SP, N450 generally does not reflect post-conflict adjustments of cognitive control (Larson, Clayson, & Clawson, 2014).

In the present study, we used event-related potentials to determine at what point in time sequential modulations of poorer-strategy effects occurred. We expected that trial-to-trial adjustments will occur between 200 and 550 ms, as previous studies found sequential effects during strategy execution to occur in this latency window (Uittenhove et al., 2013). Such adjustments were expected to appear as larger amplitudes for current poorer-strategy problems when a better-strategy is executed on the previous problem compared to following a poorer-strategy (Clayson & Larson, 2011a,b; Larson, Clayson, et al., 2012; Larson, South, et al., 2012; Tang, Hu, Li, et al., 2013). Indeed, in better–poorer trials, executive control mechanisms are not engaged after encoding the problem to monitor subsequent interference, and additional executive control resources will be required to monitor conflict. Moreover, we expected this modulation to be lateralized in left hemisphere of the brain, given the involvement of this hemisphere in mental calculation (Kiefer & Dehaene, 1997; Stanescu-Cosson et al., 2000). Considering the longer duration of our task compared to conflict tasks, we also expected later modulations associated with cognitive control. The use of ERP, a high temporal resolution technique, was also expected to determine whether sequential modulations of poorer-strategy effects occurred during stimulus encoding phases, central mechanisms of strategy execution (i.e,, retrieval of strategy procedure, calculation processes), or subsequent processes (e.g., executing procedures within each strategies).

2. Method

2.1. Participants

Twenty right-handed adults were paid 15 Euros to participate (11 females, aged from 18 to 28 years, 21.91 ± 3.12, mean ± SD). All reported normal or corrected-to-normal vision. All participants gave written informed consent. In addition, the volunteers were unaware of the purpose of the experiment.

2.2. Stimuli

Each of the 208 trials was made of two consecutive two-digit multiplication problems (e.g., 48 × 72), followed by a series of five