The Sources of Sequential Modulations of Control Processes in Arithmetic Strategies: A Magnetoencephalography Study

Thomas Hinault, Jean-Michel Badier, Sylvain Baillet, Patrick Lemaire

To cite this version:

Thomas Hinault, Jean-Michel Badier, Sylvain Baillet, Patrick Lemaire. The Sources of Sequential Modulations of Control Processes in Arithmetic Strategies: A Magnetoencephalography Study. Journal of Cognitive Neuroscience, 2017, 29 (6), pp.1033-1043. 10.1162/jocn_a_01102. hal-04502718

The Sources of Sequential Modulations of Control Processes in Arithmetic Strategies: A Magnetoencephalography Study

Article *in* Journal of Cognitive Neuroscience · February 2017

DOI: 10.1162/jocn_a_01102

4 authors:

Thomas Hinault
French Institute of Health and Medical Research
36 PUBLICATIONS 164 CITATIONS
SEE PROFILE

Jean-Michel Badier
Aix-Marseille Université
111 PUBLICATIONS 2,504 CITATIONS
SEE PROFILE

Sylvain Baillet
McGill University
232 PUBLICATIONS 8,558 CITATIONS
SEE PROFILE

Patrick Lemaire
Aix-Marseille Université
163 PUBLICATIONS 3,894 CITATIONS
SEE PROFILE

The Sources of Sequential Modulations of Control Processes in Arithmetic Strategies: A Magnetoencephalography Study

Thomas Hinault[1], **Jean-Michel Badier**[2,3], **Sylvain Baillet**[4], and **Patrick Lemaire**[1]

Abstract

■ In a wide variety of cognitive domains, performance is determined by the selection and execution of cognitive strategies to solve problems. We used magnetoencephalography to identify the brain regions involved and specify the time course of dynamic modulations of executive control processes during strategy execution. Participants performed a computational estimation task in which they were instructed to execute a poorer or better strategy to estimate results of two-digit multiplication problems. When participants were asked to execute the poorer strategy, two distinct sets of brain activations were identified, depending on whether the poorer strategy (engaging the left inferior frontal junction) or the better strategy (engaging ACC) had been executed on the immediately preceding items. Our findings also revealed the time course of activations in regions involved in sequential modulations of cognitive control processes during arithmetic strategy execution. These findings point at processes of proactive preparation on items after poorer strategy items and dynamics of reactive adjustments after better strategy items. ■

INTRODUCTION

In arithmetic, akin to other cognitive tasks, several strategies can be used to solve a given problem. Performance outcomes are determined by the strategies selected and executed on each problem (see Lemaire, 2015; Siegler, 2007, for reviews). 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 key question remains concerning how strategy selection and execution on a current problem are influenced by the strategy used for solving the preceding problem. Several computational theories of strategic processing posit strategy independence (Rieskamp & Otto, 2006; Siegler & Araya, 2005; Lovett & Schunn, 1999; Lovett & Anderson, 1996; Payne, Bettman, & Johnson, 1993), whereby strategies are selected and executed on a problem-by-problem basis, independently of the strategies previously selected and executed. However, several effects of sequential modulations of cognitive control processes during strategy execution were recently reported and are not compatible with this hypothesis (e.g., Hinault, Lemaire, & Phillips, 2016; Hinault, Dufau, & Lemaire, 2014; Lemaire & Hinault, 2014). The neural correlates underlying these behavioral effects are still poorly identified and largely unknown. Our objective was to unveil these brain processes with a focus on sequential modulations of poorer strategy effects (e.g., Hinault, Lemaire, & Phillips, 2016; Hinault et al., 2014; Lemaire & Hinault, 2014).

Poorer strategy effects (e.g., Lemaire & Leclère, 2014; Ardiale, Hodzik, & Lemaire, 2012) refer to degraded performance when the cued strategy is not the most adapted to the characteristics of the problem, compared with when participants can execute the better strategy (i.e., yielding the most accurate estimate). The magnitude of these poorer strategy effects was found to be modulated by the strategy used on the immediately preceding problem. Indeed, sequential modulations of poorer strategy effects (Hinault, Lemaire, & Phillips, 2016; Hinault et al., 2014; Lemaire & Hinault, 2014) are defined as decreased poorer strategy effects on a problem after a poorer strategy was used to solve the immediately preceding problem, compared with when the better strategy was executed. For example, Lemaire and Hinault (2014) instructed participants to estimate the products of multiplication problems using two possible approximation strategies: (a) the rounding down–up strategy, in which the first operand is rounded down to the nearest decade and the second one is rounded up to the nearest decade (e.g., 40 × 70 as an approximate for 41 × 68), and (b) the rounding up–down strategy, in which the first operand is rounded up to the nearest decade and the second one is rounded down to the nearest decade (e.g., 40 × 70 as an approximate for 38 × 72). This experimental design enables the study of processes that modulate strategy execution without being influenced by strategy selection bias. The better strategy

---

[1]Aix-Marseille Université & CNRS, Marseille, France, [2]Aix-Marseille Université & INS, Marseille, France, [3]INSERM U1106, Marseille, France, [4]McConnell Brain Imaging Centre, Montreal Neurological Institute, McGill University, Canada

Journal of Cognitive Neuroscience X:Y, pp. 1–11
doi:10.1162/jocn_a_01102

depended on operands' unit digits. For instance, using the rounding down–up strategy to estimate 41 × 68 (e.g., 40 × 70) yields a better approximation than the rounding up–down strategy (e.g., 50 × 60). Performance is decreased when the cued strategy was the poorer (see also Lemaire & Leclère, 2014; Ardiale & Lemaire, 2012; Lemaire, Arnaud, & Lecacheur, 2004; Geary, Frensch, & Wiley, 1993). Importantly, poorer strategy effects on current problems were smaller when the previous problem was solved with the poorer strategy compared with after the execution of the better strategy.

Sequential modulations of poorer strategy effects are assumed to result from modulations of cognitive control processes during strategy execution. They share important similarities with congruency sequence effects in conflict tasks (such as the Stroop, Simon, or flanker tasks). In these latter, congruency effects (i.e., poorer performance on incongruent items relative to congruent items) are smaller on items after incongruent items compared with those after congruent items (Gratton, Coles, & Donchin, 1992; see Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014, for a review). Congruency sequence effects have been interpreted as resulting from conflict detection and resolution on previous incongruent items. It is hypothesized that cognitive control processes are in a higher state of activation and/or reactivated when the next item is presented, yielding more efficient conflict processing than when the previous item was congruent (De Pisapia & Braver, 2006; Botvinick, Braver, Barch, Carter, & Cohen, 2001; see also Duthoo et al., 2014; Scherbaum, Dshemuchadse, Ruge, & Goschke, 2012, for alternative views).

Similarly, poorer strategy effects are interpreted as resulting from the necessity to inhibit the better strategy (i.e., most immediately activated upon problem presentation) to use the required poorer strategy. Indeed, previous studies using computational estimation tasks showed that participants use almost exclusively the better strategy (e.g., Hodzik & Lemaire, 2011) and that performances decline when a strategy other than the better strategy is cued (e.g., Lemaire & Brun, 2014; Ardiale & Lemaire, 2012). Such differences were correlated with measures of inhibition (e.g., with the Simon task; Hinault, Lemaire, & Touron, 2016). Furthermore, recent EEG studies (Hinault, Lemaire, & Phillips, 2016; Hinault et al., 2014) revealed ERP components associated with response conflict (e.g., P3, conflict SP) when the poorer strategy was cued. Therefore, it appears that (a) one preferred arithmetic strategy is more automatically selected than others and (b) inhibition is required when this strategy cannot be used. These executive control processes are more efficient on problems presented subsequently (Lemaire & Hinault, 2014; see also Hinault, Lemaire, & Phillips, 2016; Hinault et al., 2014). Conversely, after execution of the better strategy, executive control processes are less activated or not even involved. Therefore, they are expected to be more strongly engaged on the current poorer strategy problems. Importantly, to observe these modulations during arithmetic processing suggests that processes similar to those involved in congruency sequence effects may also be implemented in complex, multistep arithmetic tasks and are not specific to conflict tasks. However, the spatial–temporal dynamics of the cerebral activity underlying these processes are still unknown. To clarify these aspects would contribute to better assess the similarity between the processes involved in conflict versus arithmetic tasks.

fMRI results in conflict tasks revealed that congruency sequence effects involved several specific brain regions. Brain activations maps during the processing of incongruent items differed depending on whether the previous item was congruent or incongruent. ACC was more activated during congruent–incongruent sequences (i.e., a congruent item followed by an incongruent item). Furthermore, activation of the dorsolateral pFC (DLPFC) was stronger on incongruent–incongruent sequences (i.e., an incongruent item followed by an incongruent item). ACC has been assumed to reflect conflict detection and resolution (e.g., Iannaccone et al., 2015; Wang et al., 2015; Torres-Quesada, Funes, & Lupiáñez, 2013; Żurawska vel Grajewska, Sim, Hoenig, Herrnberger, & Kiefer, 2011; Etkin, Egner, Peraza, Kandel, & Hirsch, 2006; Kerns, 2004; Jones & Cho, 2002; Carter et al., 2000). Activations of the DLPFC have been interpreted as reflecting active preparation and control maintenance (e.g., Kim, Johnson, & Gold, 2014; Wang et al., 2014; Wittfoth, Schardt, Fahle, & Herrmann, 2009; Kerns, 2006; Egner & Hirsch, 2005).

The activation of these brain areas and their association with cognitive control have been discussed in the dual-mechanism framework (Braver, Paxton, Locke, & Barch, 2009; Braver, Gray, & Burgess, 2007; see Braver, 2012, for a review). This framework distinguishes between proactive and reactive modes of control. In proactive control, goal-relevant information is actively maintained in preparation for the occurrence of subsequent conflicting events. Thus, proactive control enables efficient conflict processing after the processing of an incongruent item. Reactive control consists in the detection and resolution of an interference after the encoding of a conflicting event. Thus, reactive control enables the recruitment of additional control mechanisms when participants did not prepare themselves to process conflict. fMRI studies revealed that proactive control was associated with sustained and/or anticipatory activations of the lateral pFC, whereas reactive control was associated with a transient activation of the lateral PFC together with other brain regions such as ACC (e.g., Braver, 2012; Braver et al., 2009).

In summary, previous works investigated the neural correlates of sequential modulations of cognitive control processes. EEG studies detailed the time course of these processes (e.g., Larson, Clawson, Clayson, & South, 2012; Larson, Clayson, & Baldwin, 2012; Clayson & Larson, 2011a, 2011b; Forster, Carter, Cohen, & Cho, 2011). fMRI works furthered our knowledge about the brain areas specifically involved in sequential modulations of cognitive control processes (e.g., Iannaccone et al., 2015; Kim et al., 2014; Wang et al., 2014; Kerns, 2004, 2006). Still, the dynamics of brain activations in this context remains unknown, and questions related to when these regions may be selectively activated (e.g., during or after problem encoding) to enable efficient sequential modulations of cognitive control processes need to be addressed. Furthermore, how cognitive control processes are implemented during arithmetic strategy processing needs to be clarified. Magnetoencephalography (MEG) source imaging has the unique advantage of combining both excellent temporal and spatial resolutions and can address these important questions.

We hypothesized that increased activations of ACC are observed in better–poorer sequences relative to poorer–poorer sequences. These activations would be consistent with conflict detection when cognitive control processes are in a low state of activation or not involved. We also expected to measure increased activations immediately after the encoding of the second problem in a sequence, in line with previous studies showing that P3 (i.e., centroparietal positive deflection peaking between 350 and 500 msec poststimulus) and N450 (i.e., centroparietal negativity peaking at around 450 msec after stimulus onset) ERP components are generated in ACC (e.g., Crottaz-Herbette & Menon, 2006; West, 2003; Ardekani et al., 2002; Liotti, Woldorff, Perez, & Mayberg, 2000). These effects were expected to be observed in two temporal windows, consistent with previous EEG findings (Hinault, Lemaire, & Phillips, 2016; Hinault et al., 2014). Moreover, stronger activations of DLPFC were expected in poorer–poorer sequences relative to better–poorer sequences. These activations would be consistent with the implementation of cognitive control processes after the execution of the poorer strategy on the first problem. On poorer–poorer sequences, DLPFC activations were expected to be observed during the encoding of the second problems or even before their presentation. Indeed, in such sequences, conflict has already been detected on the previous problem, and participants should prepare themselves to process conflict more efficiently on the next problem. Alternatively, the implementation of executive control could involve other left frontal areas instead of DLPFC, as proactive control was also associated with activations of other brain areas, such as the left inferior frontal junction (LIFJ; e.g., Braver et al., 2009; Brass, Derrfuss, Forstmann, & von Cramon, 2005).

METHODS

Participants

Eighteen right-handed volunteers (four men; mean age = 22.1 years, range = 18–29 years) participated in the study. A written informed consent was obtained from each participant before the experiment. Four participants were removed from the analyses: Two participants had accuracy at chance (average accuracy = 53.8%) in at least one condition, and two other participants had poor MEG signal quality.

Stimuli

A computational estimation task was used. Participants were asked to estimate the products of multiplication problems. Each of the 208 sequences was made of two consecutive two-digit multiplication problems (e.g., 48 × 72). After previous findings in arithmetic (see Campbell, 2005; Geary, 1994, for reviews), we controlled the following factors: (a) no operand had a zero unit digit; (b) no operand had five as the unit digit; (c) no digits were repeated within operands; (d) no reverse orders of operands were used; (e) the first operand was larger than the second in half of the problems, and vice versa in the other problems; (f) no operand had its closest decade equal to 0, 10, or 100; (g) differences between correct products and estimates were matched across strategies (i.e., mean percent deviations were identical between the mixed-rounding up–down and down–up strategies on all problems); and (h) rounded operands were never the same across the two problems of a given sequence. Sequences were followed by the visual presentation of five-letter strings (e.g., “aevbc”). Half of the five-letter strings included either consonants or vowels exclusively, and half included both types of letters.

Half of the problems were mixed-rounding up–down problems, and half were mixed-rounding down–up problems. The unit digit of the first operand was smaller than five, and that of the second operand was larger than five in the mixed-rounding down–up problems (e.g., 54 × 36). It was the opposite for the mixed-rounding up–down problems (e.g., 46 × 72). Two types of problems were considered: better strategy and poorer strategy problems. On better strategy problems, the cued strategy matched the problem type: Mixed-rounding down–up problems were cued with the mixed-rounding down–up strategy (e.g., doing 50 × 40 to estimate 54 × 36), and mixed-rounding up–down problems were cued with the mixed-rounding up–down strategy (e.g., doing 50 × 70 to estimate 46 × 72). Conversely, the cued strategy and the problem type differed on poorer strategy problems. Poorer strategy and better strategy problems were matched on correct products and mean percent deviations between correct products and estimates.

Four types of sequence were presented (see Table 1): better–better sequences (i.e., both current and previous problems were solved with the better strategy), better–poorer sequences (i.e., current problems were solved with the poorer strategy, and previous problems were solved with the better strategy), poorer–better sequences (i.e., current problems were solved with the better strategy, and previous problems were solved with the poorer strategy), and poorer–poorer sequences (i.e., both current and previous problems were solved with the poorer

Table 1. The Four Types of Sequences Used in the Study

Sequences	*Better–Better*	*Better–Poorer*	*Poorer–Better*	*Poorer–Poorer*
Previous problem	34 × 68 (DU)	26 × 72 (UD)	27 × 76 (DU)	68 × 83 (DU)
Current problem	67 × 82 (UD)	21 × 67 (UD)	23 × 69 (DU)	32 × 69 (UD)

Sequences are defined by the cued strategy on the previous problem (better, poorer) and on the current problem (better, poorer). The letters indicate whether the down–up (DU) strategy or the up–down (UD) strategy is cued.

strategy). Strategy repetition and alternation were controlled. The cued strategy was identical for both problems in half of the sequences and different in the other sequences. This resulted in equal proportions of switch and no-switch trials in each condition. This design was used to prevent any alternative interpretation of sequential effects in terms of cue-switch costs. Indeed, this design enables to determine whether sequential modulations differ or are similar when the cued strategy is identical or different within sequences.

Procedure

The experiment was implemented using the E-Prime software (Psychology Software Tools [1999], Pittsburgh, PA). Each sequence began with a blank screen for 500 msec, followed by a warning signal (*) presented for 400 msec in the center of the screen (see Figure 1). The problem and the cue were then displayed simultaneously on the computer screen. The cue appeared 2 cm above the problem. Both the problem and the cue remained on the screen until participants' response. The letter string "BH" (standing for "down–up" in French) cued participants to use the mixed-rounding down–up strategy, whereas "HB" (standing for "up–down" in French) cued them to use the mixed-rounding up–down strategy. Participants provided their response aloud. To reduce MEG signal contamination by speech articulation, participants were asked to vocalize only their final answer, after which the next problem was manually triggered by the experimenter. We used this procedure following previous studies that showed that it is valid to investigate relative strategy performance in general and sequential modulations of poorer strategy effects in particular, as investigated here (e.g., Lemaire & Hinault, 2014; Uittenhove, Poletti, Dufau, & Lemaire, 2013; Ardiale & Lemaire, 2012; Siegler, 2007; Lemaire et al., 2004). Errors in strategy selection were defined as participants not using the cued strategy. Errors in strategy execution were defined as participants failing to correctly execute the procedures of the cued strategy. After the participants' oral response, a blank screen was presented for 500 msec, followed by an asterisk (*) warning signal for 400 msec. The second problem of a sequence, with the corresponding cue, was then presented. A blank screen followed the participant's response (500-msec duration). Then, after a 500-msec blank screen, an asterisk (*) appeared for 400 msec, followed by a five-letter string (e.g., "aeiou"). Participants had to press the "L" key on an AZERTY keyboard if all letters were either vowels or consonants or the "S" key if letters included both vowels and consonants. Following previous works (Lemaire & Hinault, 2013; Uittenhove et al., 2013; Ardiale et al., 2012; Uittenhove & Lemaire, 2012; Lemaire & Lecacheur, 2010), this letter judgment task avoids interference between the last problem of a sequence and the first problem of the next sequence. A 1000-msec blank screen was displayed before the next sequence started.

The MEG experiment consisted of four blocks of 52 sequences each, with 5-min breaks between blocks. The order of presentation was counterbalanced across participants. Each session lasted about 45–60 min. Participants were instructed to estimate the product of multiplication problems as fast and accurately as possible using only the cued strategy. The two mixed-rounding strategies were then explained to participants. The mixed-rounding down–up strategy was described as 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. The mixed-rounding up– down strategy was described as rounding the first operand up to the nearest decade and the second operand down to nearest decade, for instance, doing 40 × 60 to estimate 38 × 64. The participants started with a practice phase consisting of eight problems (four with each strategy). Then, the practice phase included eight sequences (each involving two multiplication problems and a series of five letters).

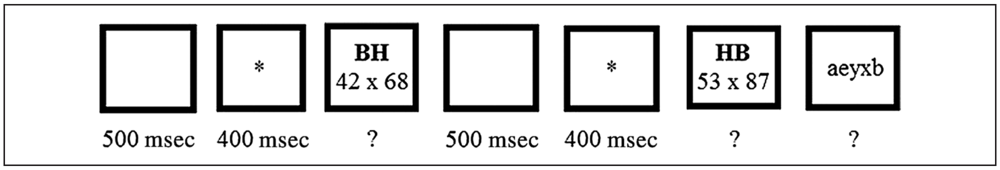

Figure 1. Events within a sequence. The letters "BH" (i.e., standing for "down–up" in French) cued participants to use the mixed-rounding down–up strategy, and the letters "HB" (i.e., standing for "up–down" in French) prompted participants to use the mixed-rounding up–down strategy. The "?" indicates when, in the sequence, participant's response was expected and that these screens remain until the participant has responded.

MEG Recording

The data were acquired at the La Timone Hospital in Marseille, using a 248-channel whole-head 4D neuroimaging MEG system, at a sampling rate of 2035 Hz. The EOG and the electrocardiogram were recorded to capture eye movements and heartbeats, respectively. Five head-positioning coils were attached to the forehead and to the periauricular points to determine the position of the head. The individual head shape, consisting of the forehead, nose, and the location of the head-position coils, was digitized (Polhemus Fastrak; Polhemus Inc., Colchester, VT). Participants were lying on a hospital bed inside a magnetically shielded room. Stimuli were presented on a 800 × 600 resolution screen placed about 45 cm above participants, using a 48-point bold Courier font (black color), using a standard video projector. The visual angle was 1.4°. Head position inside the MEG helmet was measured at the beginning of every block. Head displacements were monitored for remaining under 5 mm within each block. The exact timing of visual presentation was captured using photo-diodes that detected brightness changes on the presentation screen.

MEG Analysis

Artifact and channel rejection (on continuous data), filtering (0.1- to 20-Hz bandpass, on unepoched data), time segmentation into 12.40-sec epochs, averages, and source estimation were all performed using Brainstorm (Tadel, Baillet, Mosher, Pantazis, & Leahy, 2011). Continuous data were visually inspected to identify physiological (e.g., blinks, saccades, heartbeats) and nonphysiological (e.g., bad sensors) artifacts. Epoching of problems was time-locked to the onset of the first problem and included 400 msec of prestimulus baseline. We selected this period as baseline, as the period before the second problems of a sequence was assumed to be influenced by the processing of the first problem. Artifact-free epochs were extracted from −400 to 1500 msec around the second problems of a sequence. Artifact-free epochs for each experimental condition were averaged separately to obtain ERFs in each participant.

A free orientation, cortically constrained minimum norm estimation (MNE) procedure was applied to estimate the cortical origin of the brain responses (Hauk, 2004; Hämäläinen & Ilmoniemi, 1994). The MNE was weighted by a sample estimate of sensor noise covariance matrix (Dale et al., 2000) obtained from 30 sec of empty room recording, in each of the participants, and used for improved data modeling, as typical in MNE approaches (Baillet, Mosher, & Leahy, 2001). The MEG forward model was obtained from overlapping spheres fitted to each participant's scalp points (Huang, Mosher, & Leahy, 1999). For all participants, sources were constrained to a cortical surface mesh template obtained from the MNI Colin 27 brain. Brainstorm was used with default parameters to warp the template to each participant's digitized head shape (see Leahy et al., 1998, for technical details). The norm of the three source time series at each cortical voxel (i.e., conversion of orientation–unconstrained sources to flat maps, taking the norm of the three elementary dipoles at each time step, yielding only one value by vertex) was extracted and z scored with respect to the prestimulus ([−400, 0] msec) baseline.

We defined three ROIs, based on previous findings (e.g., Kim et al., 2014; Wang et al., 2014; Braver et al., 2009; Kerns, 2006; Brass et al., 2005; Yeung et al., 2004; West, 2003; Van Veen & Carter, 2002): (1) left ACC (coordinates of the ROI's centroid, MRI coordinates: $x = 91$, $y = 162$, and $z = 92$; 13 vertices, 2.17-cm^2 spatial extent over cortex), (2) left DLPFC ($x = 52, y = 175$, and $z = 83$; 21 vertices, 3.71 cm^2), and (3) LIFJ ($x = 34, y = 125$, and $z = 94$; 29 vertices, 4.13 cm^2). A whole-brain t test ($p <$ .001, uncorrected) was run to determine whether significant activations were present in other brain areas than the ROIs. No significant activation lasting at least 50 msec was observed elsewhere. For the three ROIs, differences in source activation on current poorer strategy problems, as a function of the execution of a previous better or poorer strategy (time-locked to the onset of the second problem), were tested for significance using permutations of problems across conditions ($n = 1000$), with cluster-based correction to correct for multiple comparisons (Maris & Oostenveld, 2007). In line with previous neuroimaging studies on sequential modulations of cognitive control processes (e.g., Kerns, 2004), we compared better–poorer sequences (i.e., the current problem was solved with the poorer strategy, and the previous problem was solved with the better strategy) with poorer–poorer sequences (both current and previous problems were solved with the poorer strategy). The rationale for contrasting these two sequences was that poorer–poorer and better–poorer sequences were expected to reveal distinct neurophysiological patterns on current poorer strategy problems, as a function of the strategy executed on previous problems.

RESULTS

Behavioral Results

Mean estimation times and error rates in strategy selection and strategy execution on the second problems of a sequence were analyzed using 2 (Strategy on the previous problem: better, poorer) × 2 (Strategy on the current problem: better, poorer) within-participant ANOVAs. To correct for multiple comparisons, Sidak correction was applied.

The main effect of Strategy on the previous problem was not significant ($F < 1.0$). However, participants were slower on current poorer strategy problems than on current better strategy problems (5047 vs. 4834 msec), $F(1, 13) = 9.48$, $p < .01$, $MSE = 49000.26$, $\eta_p^2 = .42$. Moreover, the Strategy on the previous problem × Strategy

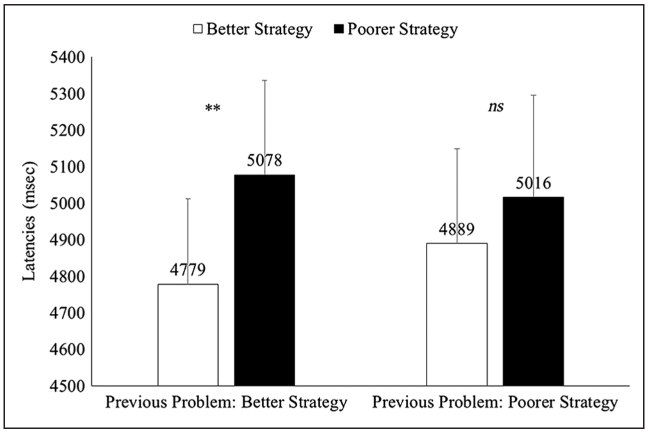

Figure 2. Mean solution times for current better strategy and poorer strategy problems after better strategy or poorer strategy problems. Error bars represent *SEM*. *$p < .05$. **$p < .01$. ***$p < .001$.

on the current problem interaction was significant, $F(1, 13) = 5.88$, $p < .03$, $MSE = 8007.18$, $\eta_p^2 = .31$ (see Figure 2). Planned comparisons revealed that the difference between better–better and better–poorer sequences was significant (300 msec; $F(1, 13) = 15.84$, $p < .01$, $MSE = 75.26$, $\eta_p^2 = .55$), whereas poorer–better and poorer–poorer sequences did not differ (127 msec; Fs < 2.5). Analyses of errors in strategy execution and selection revealed no significant main or interaction effects (Fs $<$ 1.5). In addition to sequential modulations of poorer strategy effects, a significant difference was observed between better–poorer and poorer–poorer sequences ($F(1, 13) = 8.07$, $p < .02$, $MSE = 115.19$, $\eta_p^2 = .38$), whereas no differences were found between better–better and poorer–better sequences ($F < 1.0$). Thus, the strategy executed on the first problem was a strong determinant of participants' performance when they executed a poorer strategy on the next problem.

To rule out an explanation of the observed sequential modulations in terms of cue-switch costs, additional analyses were performed using 2 (Cued strategy: repeated, unrepeated) × 2 (Strategy on the previous problem: better, poorer) × 2 (Strategy on the current problem: better, poorer) within-participant ANOVAs. Analyses of RTs and errors did not reveal any main effects or interactions involving this strategy-repetition/switch factor (Fs < 2.5).

MEG Results

The MEG analyses focused on comparing activations on current poorer strategy problems, as a function of whether previous problems were solved with the better or poorer strategy. Indeed, behavioral analyses revealed significant differences between these sequences, although participants obtained similar performance on better–better and poorer–better sequences. Cluster-based permutation tests revealed significant differences in brain activations during the execution of the poorer strategy, as a function of the strategy previously executed, in two ROIs (see Figure 3; only clusters that reached the significance threshold are displayed). Larger amplitudes were found in LIFJ for poorer–poorer sequences relative to better–poorer sequences between −400 and 15 msec, before the second problems' display ($p < .05$; see Figure 4). Two regional clusters were also found in left ACC, with larger amplitudes for better–poorer sequences than poorer–poorer sequences between 150 and 915 msec ($p < .02$) and between 950 and 1500 msec ($p < .04$), relative to onset of the second problems (Figure 5). Activations in DLPFC were not found to differ significantly as a function of the strategy executed on previous problems (ps > 1.0).

To specify the differential timing of activations in ACC and LIFJ, we conducted a 2 (Strategy on the previous problem: better, poorer) × 2 (ROI: ACC, LIFJ) × 38 (Time: mean of 50-msec time windows) repeated-measure ANOVA. Planned comparisons (false discovery rate corrected) were conducted to investigate significant interactions. There was a main effect of ROI, with larger activations for ACC than for LIFJ ($F(1, 13) = 5.92$, $p < .04$, $MSE = 905.04$, $\eta_p^2 = .31$). Furthermore, the Strategy on the previous problem × ROI interaction was significant ($F(1, 13) = 13.63$, $p < .01$, $MSE = 5630557.91$, $\eta_p^2 = .51$), with larger activation of ACC when the better strategy was executed on the previous problem, whereas LIFJ was

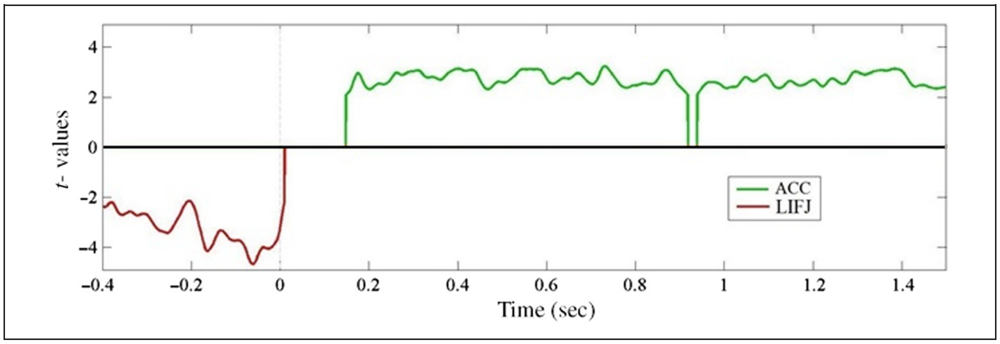

Figure 3. Results of cluster-based permutation tests (on current poorer strategy trials after better strategy vs. after poorer strategy trials) in ACC and LIFJ. Plotted are t values from −400 to 1500 msec (time-locked to the onset of the second problem). The red line represents significantly larger activations in LIFJ cluster on current poorer strategy trials after poorer strategy trials compared with after better strategy problems. The green line represents significantly larger activations in ACC clusters on current poorer strategy trials after better strategy trials compared with after poorer strategy trials. Only clusters that reached the significance threshold are displayed.

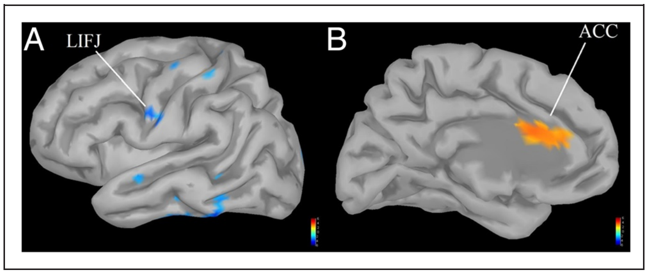

Figure 4. Differences in *z*-scored amplitudes for LIFG (A) and for ACC (B) on current poorer strategy trials, between previous better strategy trials, and after previous poorer strategy trials. Blue represents larger activations after poorer strategy trials, whereas yellow represents larger activations after better strategy trials.

more activated after the execution of the poorer strategy. The ROI × Time interaction was also significant ($F(37, 481) = 2.17$, $p < .01$, $MSE = 7428.41$, $\eta_p^2 = .14$), with larger activations during the presentation of the second problem for ACC than for the LIFJ. Importantly, the Strategy on the previous problem × ROI × Time interaction was also significant ($F(37, 481) = 1.52$, $p < .03$, $MSE = 1902.52$, $\eta_p^2 = .11$). Planned comparisons (Table 2) revealed that activations of ACC were significantly larger after the execution of the better strategy than after the poorer strategy between 150 and 900 msec and between 950 and 1500 msec. Moreover, activations of the LIFJ were significantly larger after execution of the poorer strategy than after the better strategy between −400 and 0 msec.

DISCUSSION

In this study, we took advantage of the excellent temporal and spatial resolutions of MEG to study the spatial–temporal dynamics of brain activations engaged in sequential modulations of cognitive control processes. Participants were asked to perform a computational estimation task in which they were required to execute either a better or poorer strategy to provide estimates. No effect of strategy repetitions was found, which rules out an explanation of the present findings in terms of switch costs. We replicated previously found behavioral sequential modulations of poorer strategy effects, with reduced poorer strategy effects on a given problem after execution of the poorer rather than the better strategy (Hinault et al., 2014; Lemaire & Hinault, 2014). These results suggest that participants accomplished the computational estimation task in the same manner in the MEG than outside the scanner. Although the task used here differed from conflict tasks in terms of latency and processes involved, this study, together with previous research (see Hinault & Lemaire, 2016, for a review), furthers our understanding of the cognitive control processes involved in the execution of arithmetic strategies. Indeed, the cognitive control processes previously studied in conflict tasks appear to be implemented similarly in complex, multistep arithmetic tasks. Our findings

Table 2. Results of Planned Comparisons (FDR Corrected) for the Strategy on the Previous Problem × ROI × Time Interaction

ROIs	*Latencies*	*F(1, 13)*	*p*	*MSE*	η_p^2
LIFJ	−400/−350 msec	7.70	<.02	111.30	.37
	−350/−300 msec	8.53	<.02	120.28	.40
	−300/−250 msec	12.01	<.01	110.60	.48
	−250/−200 msec	8.66	<.02	122.36	.40
	−200/−150 msec	10.68	<.01	117.29	.45
	−150/−100 msec	11.45	<.01	118.12	.47
	−100/−50 msec	12.88	<.01	120.13	.50
	−50/0 msec	11.46	<.01	135.78	.47
ACC	150/200 msec	6.59	<.03	162.32	.34
	200/250 msec	6.35	<.03	170.94	.33
	250/300 msec	8.86	<.02	146.54	.41
	300/350 msec	8.89	<.02	138.69	.41
	350/400 msec	8.93	<.02	141.04	.41
	400/450 msec	9.26	<.01	161.92	.42
	450/500 msec	6.66	<.03	169.78	.34
	500/550 msec	8.42	<.02	165.82	.39
	550/600 msec	9.88	<.01	155.75	.43
	600/650 msec	7.73	<.02	172.91	.37
	650/700 msec	8.24	<.02	170.76	.39
	700/750 msec	8.86	<.02	157.34	.41
	750/800 msec	6.70	<.03	174.61	.34
	800/850 msec	7.10	<.02	184.67	.35
	850/900 msec	8.57	<.02	170.75	.40
	950/1000 msec	6.95	<.03	200.44	.35
	1000/1050 msec	6.96	<.03	194.69	.35
	1050/1100 msec	7.94	<.02	194.22	.38
	1100/1150 msec	7.04	<.03	195.93	.35
	1150/1200 msec	7.04	<.02	187.75	.36
	1200/1250 msec	7.95	<.02	161.70	.38
	1250/1300 msec	8.47	<.02	166.85	.39
	1300/1350 msec	9.70	<.01	180.30	.43
	1350/1400 msec	10.26	<.01	181.52	.44
	1400/1450 msec	7.69	<.02	197.96	.37
	1450/1500 msec	6.95	<.03	204.24	.35

Results revealed significant differences as a function of the strategy previously executed for several latencies in each ROI. Differences consisted in larger activations when the poorer strategy was previously executed for LIFJ, whereas activations were larger after execution of the better strategy in ACC. FDR = false discovery rate.

reveal the location and time course of the cerebral regions underlying sequential modulations of poorer strategy effects. ACC and LIFJ were found to be involved during sequential modulations of poorer strategy effects, with distinct time courses. These results have important implications for our understanding of executive control processes involved in arithmetic strategy execution.

In contrast with previous studies that investigated the time course of arithmetic problem solving (e.g., Tschentscher & Hauk, 2016; Bemis & Pylkkanen, 2013), we investigated specifically the cognitive control processes involved during strategy execution. Therefore, as the characteristics of the second problem were kept constant between the two main conditions, the neural bases of arithmetic problem solving were not studied. Results support the implication of executive control processes in sequential modulations of strategy execution. Lemaire and Hinault (2014) proposed that sequential modulations of poorer strategy effects involved the same mechanisms as those assumed by theories of executive control (De Pisapia & Braver, 2006; Botvinick et al., 2001; see Scherbaum et al., 2012; Mayr & Awh, 2008, for alternative views). More specifically, poorer strategy problems were hypothesized to elicit inhibition of the tendency to execute the better strategy, triggered by problems features (i.e., size of unit digits). Increased activations of executive control processes would then yield more efficient conflict processing on the next problem. Conversely, after the execution of the better strategy, executive control processes are less involved, resulting in less efficient conflict processing on the next problem. Our results are consistent with previous observations in conflict tasks and are consistent with the hypothesis proposed by Lemaire and Hinault (2014). Furthermore, this study adds converging evidence in favor of the hypothesis that cognitive control processes similar to those observed in conflict tasks are involved during sequential modulations of arithmetic strategies.

Larger ACC activations were observed during the second problems of a sequence, when previous problems were solved with the better rather than the poorer strategy, in two temporal windows (i.e., between 150 and 900 msec and between 950 and 1500 msec). ACC had been identified in conflict tasks in association with conflict detection and resolution (e.g., Wang et al., 2015; Torres-Quesada et al., 2013; Kerns, 2004) as well as with reactive control (e.g., Braver, 2012; Braver et al., 2009). Our results are consistent with executive control processes being less activated during and after the execution of the better strategy. Hence, on the next problem, additional control processes need to be implemented to inhibit the automatic tendency of activating the better strategy and executing the procedures of the required poorer strategy. The two time windows are similar to those reported in previous ERP results (Hinault et al., 2014). Several ERP components observed in conflict tasks, such as the P3 and N450, have been found to be generated by ACC (e.g., Crottaz-Herbette & Menon, 2006; West, 2003; Ardekani et al., 2002; Liotti et al., 2000). Although the observed time course of activation differs, we can hypothesize that Hinault et al.'s (2014) findings of larger positivity for better–poorer sequences compared with poorer–poorer sequences reflect ACC activations. This may be clarified by future studies involving simultaneous EEG and MEG recordings.

Activation of the LIFJ was found within 400 msec before the onset of the second problems. The magnitude of this activity was larger when the previous problem was solved with the poorer rather than the better strategy. The LIFJ was previously observed in conflict tasks and has been associated with proactive control (e.g., Braver et al., 2009; Brass et al., 2005; Brass & von Cramon, 2004) and maintenance of task rules (e.g., Montojo & Courtney, 2008; Roth, 2005). Our findings are consistent with participants preparing themselves proactively, after the execution of the poorer strategy on the previous problem, to execute strategies more efficiently on the next problem. Such activations before the presentation of the second problems may reflect the maintenance of inhibitory processes to efficiently suppress the tendency to use the better strategy on poorer strategy problems. This would enable participants to focus more efficiently on the cue rather than on the size of unit digits to know which strategy is required and to execute the procedures of the required strategy.

The DLPFC was not found to be involved differently as a function of the strategy executed on the previous problem. This was unexpected because this region was previously found to be involved in conflict tasks, with larger activation in incongruent–incongruent sequences than in congruent–incongruent sequences (e.g., Kim et al., 2014; Wang et al., 2014; Wittfoth et al., 2009; Kerns, 2006; Egner & Hirsch, 2005). However, it was pointed out in a meta-analysis that, in conflict tasks, the DLPFC showed less consistent patterns of activations than the LIFJ (Derrfuss et al., 2005). Moreover, a recent study on congruency sequence effects in fMRI did not report modulations of the DLPFC (Wang et al., 2015), suggesting that this brain region may not be necessary for efficient problem-by-problem modulations of cognitive control processes. Furthermore, Taillan et al. (in press) studied arithmetic strategy selection with fMRI and found that the DLPFC was more activated in a choice condition (i.e., when participants had to select one strategy) relative to a no-choice condition (i.e., when participants were required to execute a cued strategy and thus did not have to choose a strategy). Therefore, we can hypothesize that activation of the DLPFC is necessary in contexts that require strategy selection. All these reasons may explain why, in this study, the DLPFC was not found to be modulated during strategy execution.

Our results provide fine-grained neurophysiological evidence about the neural correlates and timing of the cognitive control processes involved in sequential modulations of strategy execution. Considering previous correlational and experimental evidence, our findings demonstrate the role of cognitive control processes in arithmetic strategy use. Therefore, these results have important theoretical implications toward our understanding of strategy performance. According to computational theories of strategic processing (Rieskamp & Otto, 2006; Siegler & Araya, 2005; Lovett & Schunn, 1999; Lovett & Anderson, 1996; Payne et al., 1993), strategies are selected and executed on a problem-by-problem basis, independently of strategies used on previous problems. Furthermore, cognitive control processes are not assumed to modulate strategy use and strategy execution. Our results call for a revision of these models to include mechanisms of problem-by-problem modulations during strategy selection and execution. The models should also be revised to account for the cognitive control processes involved in these sequential modulations, together with their neural correlates. Additional mechanisms would include inhibition of automatically activated strategies and activation of the procedures of the required strategy, supported by ACC. We also advocate for the inclusion of proactive preparation of cognitive control processes from one problem to the next to improve conflict processing on the next problem, supported by the LIFJ.

UNCITED REFERENCE

Muhle-Karbe et al., 2015

Acknowledgments

This work was supported in part by the Centre National de la Recherche Scientifique (French National Science Foundation) and by a grant from the Agence Nationale de la Recherche (Grant number BLAN-1912-01). This work was performed on a platform member of France Life Imaging network (Grant ANR-11-INBS-0006).

Reprint requests should be sent to Patrick Lemaire, CNRS & Aix-Marseille Université, 3 Place Victor Hugo, 13331 Marseille, France, or via e-mail: patrick.lemaire@univ-amu.fr.

REFERENCES

Ardekani, B. A., Choi, S. J., Hossein-Zadeh, G.-A., Porjesz, B., Tanabe, J. L., Lim, K. O., et al. (2002). Functional magnetic resonance imaging of brain activity in the visual oddball task. *Cognitive Brain Research, 14,* 347–356.

Ardiale, E., Hodzik, S., & Lemaire, P. (2012). Aging and strategy switch costs: A study in arithmetic problem solving. *L'Année Psychologique, 112,* 345–360.

Ardiale, E., & Lemaire, P. (2012). Within-item strategy switching: An age comparative study in adults. *Psychology and Aging, 27,* 1138–1151.

Baillet, S., Mosher, J., & Leahy, R. (2001). Electromagnetic brain mapping. *IEEE Signal Processing Magazine, 18,* 14–30.

Bemis, D. K., & Pylkkanen, L. (2013). Combination across domains: An MEG investigation into the relationship between mathematical, pictorial, and linguistic processing. *Language Sciences, 3,* 583.

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108,* 624–652.

Brass, M., Derrfuss, J., Forstmann, B., & von Cramon, D. Y. (2005). The role of the inferior frontal junction area in cognitive control. *Trends in Cognitive Sciences, 9,* 314–316.

Brass, M., & von Cramon, D. Y. (2004). Selection for cognitive control: A functional magnetic resonance imaging study on the selection of task-relevant information. *Journal of Neuroscience, 24,* 8847–8852.

Braver, T. S. (2012). The variable nature of cognitive control: A dual mechanisms framework. *Trends in Cognitive Sciences, 16,* 106–113.

Braver, T. S., Gray, J. R., & Burgess, G. C. (2007). Explaining the many varieties of working memory variation: Dual mechanisms of cognitive control. In A. R. A. Conway, C. Jarrold, M. J. Kane, A. Miyake, & J. N. Towse (Eds.), *Variation in working memory* (pp. 76–106). Oxford: Oxford University Press.

Braver, T. S., Paxton, J. L., Locke, H. S., & Barch, D. M. (2009). Flexible neural mechanisms of cognitive control within human prefrontal cortex. *Proceedings of the National Academy of Sciences, U.S.A., 106,* 7351–7356.

Carter, C. S., Macdonald, A. M., Botvinick, M., Ross, L. L., Stenger, V. A., Noll, D., et al. (2000). Parsing executive processes: Strategic vs. evaluative functions of the anterior cingulate cortex. *Proceedings of the National Academy of Sciences, U.S.A., 97,* 1944–1948.

Clayson, P. E., & Larson, M. J. (2011a). Conflict adaptation and sequential trial effects: Support for the conflict monitoring theory. *Neuropsychologia, 49,* 1953–1961.

Clayson, P. E., & Larson, M. J. (2011b). Effects of repetition priming on electrophysiological and behavioral indices of conflict adaptation and cognitive control. *Psychophysiology, 48,* 1621–1630.

Crottaz-Herbette, S., & Menon, V. (2006). Where and when the anterior cingulate cortex modulates attentional response: Combined fMRI and ERP evidence. *Journal of Cognitive Neuroscience, 18,* 766–780.

Dale, A. M., Liu, A. K., Fischl, B. R., Buckner, R. L., Belliveau, J. W., Lewine, J. D., et al. (2000). Dynamic statistical parametric mapping: Combining fMRI and MEG for high-resolution imaging of cortical activity. *Neuron, 26,* 55–67.

De Pisapia, N., & Braver, T. S. (2006). A model of dual control mechanisms through anterior cingulate and prefrontal cortex interactions. *Neurocomputing, 69,* 1322–1326.

Duthoo, W., Abrahamse, E. L., Braem, S., Boehler, C. N., & Notebaert, W. (2014). The heterogeneous world of congruency sequence effects: An update. *Frontiers in Psychology, 5,* 1001. doi:10.3389/fpsyg.2014.01001.

Egner, T., & Hirsch, J. (2005). The neural correlates and functional integration of cognitive control in a Stroop task. *Neuroimage, 24,* 539–547.

Etkin, A., Egner, T., Peraza, D. M., Kandel, E. R., & Hirsch, J. (2006). Resolving emotional conflict: A role for the rostral anterior cingulate cortex in modulating activity in the amygdala. *Neuron, 51,* 871–882.

Forster, S. E., Carter, C. S., Cohen, J. D., & Cho, R. Y. (2011). Parametric manipulation of the conflict signal and control-state adaptation. *Journal of Cognitive Neuroscience, 23,* 923–935.

Geary, D. C., Frensch, P. A., & Wiley, J. G. (1993). Simple and complex mental subtraction: Strategy choice and speed-of-processing differences in younger and older adults. *Psychology and Aging, 8,* 242.

Gratton, G., Coles, M. G., & Donchin, E. (1992). Optimizing the use of information: Strategic control of activation of responses. *Journal of Experimental Psychology: General, 121,* 480.

Hämäläinen, M. S., & Ilmoniemi, R. J. (1994). Interpreting magnetic fields of the brain: Minimum norm estimates. *Medical & Biological Engineering & Computing, 32,* 35–42.

Hauk, O. (2004). Keep it simple: A case for using classical minimum norm estimation in the analysis of EEG and MEG data. *Neuroimage, 21,* 1612–1621.

Hinault, T., Dufau, S., & Lemaire, P. (2014). Sequential modulations of poorer-strategy effects during strategy execution: An event-related potential study in arithmetic. *Brain and Cognition, 91,* 123–130.

Hinault, T., & Lemaire, P. (2016). Age-related changes in strategic variations during arithmetic problem solving: The role of executive control. *Progress in Brain Research, 227,* 257–276. doi:10.1016/bs.pbr.2016.03.009.

Hinault, T., Lemaire, P., & Phillips, N. (2016). Aging and sequential modulations of poorer strategy effects: An EEG study in arithmetic problem solving. *Brain Research, 1630,* 144–158.

Hinault, T., Lemaire, P., & Touron, D. (2016). Aging effects in sequential modulations of poorer-strategy effects during execution of memory strategies. *Memory, 17,* 1–11.

Huang, M. X., Mosher, J. C., & Leahy, R. M. (1999). A sensor-weighted overlapping-sphere head model and exhaustive head model comparison for MEG. *Physics in Medicine and Biology, 44,* 423.

Iannaccone, R., Hauser, T. U., Staempfli, P., Walitza, S., Brandeis, D., & Brem, S. (2015). Conflict monitoring and error processing: New insights from simultaneous EEG–fMRI. *Neuroimage, 105,* 395–407.

Jones, A., & Cho, R. (2002). A computational model of anterior cingulate function in speeded response tasks: Effects of frequency, sequence, and conflict. *Cognitive, Affective & Behavioral Neuroscience, 2,* 300–317.

Kerns, J. G. (2004). Anterior cingulate conflict monitoring and adjustments in control. *Science, 303,* 1023–1026.

Kerns, J. G. (2006). Anterior cingulate and prefrontal cortex activity in an fMRI study of trial-to-trial adjustments on the Simon task. *Neuroimage, 33,* 399–405.

Kim, C., Johnson, N. F., & Gold, B. T. (2014). Conflict adaptation in prefrontal cortex: Now you see it, now you don't. *Cortex, 50,* 76–85.

Larson, M. J., Clawson, A., Clayson, P. E., & South, M. (2012). Cognitive control and conflict adaptation similarities in children and adults. *Developmental Neuropsychology, 37,* 343–357.

Larson, M. J., Clayson, P. E., & Baldwin, S. A. (2012). Performance monitoring following conflict: Internal adjustments in cognitive control? *Neuropsychologia, 50,* 426–433.

Lemaire, P. (2015). *Cognitive aging: The role of strategies*. London: Psychology Press.

Lemaire, P., Arnaud, L., & Lecacheur, M. (2004). Adults' age-related differences in adaptivity of strategy choices: Evidence from computational estimation. *Psychology and Aging, 19,* 467–481.

Lemaire, P., & Hinault, T. (2014). Age-related differences in sequential modulations of poorer-strategy effects. *Experimental Psychology, 61,* 253–262.

Lemaire, P., & Lecacheur, M. (2010). Strategy switch costs in arithmetic problem solving. *Memory & Cognition, 38,* 322–332.

Lemaire, P., & Leclère, M. (2014). Strategy repetition in young and older adults: A study in arithmetic. *Developmental Psychology, 50,* 460–468.

Lemaire, P., & Reder, L. (1999). What affects strategy selection in arithmetic? The example of parity and five effects on product verification. *Memory & Cognition, 27,* 364–382.

Liotti, M., Woldorff, M. G., Perez, R., III, & Mayberg, H. S. (2000). An ERP study of the temporal course of the Stroop color-word interference effect. *Neuropsychologia, 38,* 701–711.

Lovett, M. C., & Anderson, J. R. (1996). History of success and current context in problem solving. *Cognitive Psychology, 31,* 168–217.

Lovett, M. C., & Schunn, C. D. (1999). Task representations, strategy variability, and base-rate neglect. *Journal of Experimental Psychology: General, 128,* 107.

Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods, 164,* 177–190.

Mayr, U., & Awh, E. (2008). The elusive link between conflict and conflict adaptation. *Psychological Research, 73,* 794–802.

Montojo, C. A., & Courtney, S. M. (2008). Differential neural activation for updating rule versus stimulus information in working memory. *Neuron, 59,* 173–182.

Muhle-Karbe, P. S., Derrfuss, J., Lynn, M. T., Neubert, F. X., Fox, P. T., Brass, M., et al. (2015). Co-activation-based parcellation of the lateral prefrontal cortex delineates the inferior frontal junction area. *Cerebral Cortex, 26,* 2225–2241.

Payne, J. W., Bettman, J. R., & Johnson, E. J. (1993). *The adaptive decision maker*. Cambridge: Cambridge University Press.

Rieskamp, J., & Otto, P. E. (2006). SSL: A theory of how people learn to select strategies. *Journal of Experimental Psychology: General, 135,* 207–236.

Roth, J. K. (2005). Neural system for controlling the contents of object working memory in humans. *Cerebral Cortex, 16,* 1595–1603.

Scherbaum, S., Dshemuchadse, M., Ruge, H., & Goschke, T. (2012). Dynamic goal states: Adjusting cognitive control without conflict monitoring. *Neuroimage, 63,* 126–136.

Siegler, R., & Araya, R. (2005). A computational model of conscious and unconscious strategy discovery. *Advances in Child Development and Behavior, 33,* 1–42.

Siegler, R. S. (2007). Cognitive variability. *Developmental Science, 10,* 104–109.

Tadel, F., Baillet, S., Mosher, J. C., Pantazis, D., & Leahy, R. M. (2011). Brainstorm: A user-friendly application for MEG/EEG analysis. *Computational Intelligence and Neuroscience, 2011,* 1–13.

Taillan, J., Ardiale, E., Anton, J. L., Nazarian, B., Félician, O., & Lemaire, P. (in press). How do we choose among strategies to accomplish cognitive tasks? Evidence from behavioral and ERP data in arithmetic problem solving. *Mind, Brain, and Education*.

Torres-Quesada, M., Funes, M. J., & Lupiáñez, J. (2013). Dissociating proportion congruent and conflict adaptation effects in a Simon–Stroop procedure. *Acta Psychologica, 142,* 203–210.

Tschentscher, N., & Hauk, O. (2016). Frontal and parietal cortices show different spatiotemporal dynamics across problem-solving stages. *Journal of Cognitive Neuroscience, 30,* 1–13.

Uittenhove, K., & Lemaire, P. (2012). Sequential difficulty effects during strategy execution. *Experimental Psychology, 59,* 295–301.

Uittenhove, K., Poletti, C., Dufau, S., & Lemaire, P. (2013). The time course of strategy sequential difficulty effects: An ERP study in arithmetic. *Experimental Brain Research, 227,* 1–8.

Van Veen, V., & Carter, C. S. (2002). The timing of action-monitoring processes in the anterior cingulate cortex. *Journal of Cognitive Neuroscience, 14,* 593–602.

Wang, T., Chen, Z., Zhao, G., Hitchman, G., Liu, C., Zhao, X., et al. (2014). Linking inter-individual differences in the conflict adaptation effect to spontaneous brain activity. *Neuroimage, 90,* 146–152.

Wang, X., Wang, T., Chen, Z., Hitchman, G., Liu, Y., & Chen, A. (2015). Functional connectivity patterns reflect individual differences in conflict adaptation. *Neuropsychologia, 70,* 177–184.

West, R. (2003). Neural correlates of cognitive control and conflict detection in the Stroop and digit-location tasks. *Neuropsychologia, 41,* 1122–1135.

Wittfoth, M., Schardt, D. M., Fahle, M., & Herrmann, M. (2009). How the brain resolves high conflict situations: Double conflict involvement of dorsolateral prefrontal cortex. *Neuroimage, 44,* 1201–1209.

Żurawska vel Grajewska, B., Sim, E.-J., Hoenig, K., Herrnberger, B., & Kiefer, M. (2011). Mechanisms underlying flexible adaptation of cognitive control: Behavioral and neuroimaging evidence in a flanker task. *Brain Research, 1421,* 52–65.