Frontal Cortex Supports the Early Structuring of Multiple Solution Steps in Symbolic Problem-solving

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Abstract

■ Abstract problem-solving relies on a sequence of cognitive steps involving phases of task encoding, the structuring of solution steps, and their execution. On the neural level, metabolic neuroimaging studies have associated a frontal-parietal network with various aspects of executive control during numerical and nonnumerical problem-solving. We used EEG–MEG to assess whether frontal cortex contributes specifically to the early structuring of multiple solution steps. Basic multiplication ("3 × 4" vs. "3 × 24") was compared with an arithmetic sequence rule ("first add the two digits, then multiply the sum with the smaller digit") on two complexity levels. This allowed dissociating demands of early solution step structuring from early task encoding demands. Structuring demands were high for conditions that required multiple steps, that is, complex multiplication and the two arithmetic sequence conditions, but low for easy multiplication that mostly relied on direct memory retrieval. Increased right frontal activation in time windows between 300 and 450 msec was observed only for conditions that required multiple solution steps. General task encoding demands, operationalized by problem size (one-digit vs. two-digit numbers), did not predict these early frontal effects. In contrast, parietal effects occurred as a function of problem size irrespectively of structuring demands in early phases of task encoding between 100 and 300 msec. We here propose that frontal cortex subserves domain-general processes of problem-solving, such as the structuring of multiple solution steps, whereas parietal cortex supports number-specific early encoding processes that vary as a function of problem size. ■

INTRODUCTION

The neural processes underlying human problem-solving have been extensively investigated using metabolic neuroimaging methods, whereas our knowledge on the particular neural dynamics across stages of a problem-solving process is still very limited. Metabolic neuroimaging studies have defined a core set of frontal and parietal regions, commonly involved in executive control processes during numerical reasoning (for meta-analysis, see Arsalidou & Taylor, 2011) as well as nonnumerical problem-solving (Cole et al., 2013; Dosenbach, Fair, Cohen, Schlaggar, & Petersen, 2008; Duncan & Owen, 2000). One fundamental aspect of executive control is the ability to efficiently process multiple (novel) task requirements (Bhandari & Duncan, 2014; Duncan, 2013; Gray, Chabris, & Braver, 2003), and in particular lateral frontal cortex has been associated with the temporal integration of multiple task demands in fMRI and primate electrophysiology research (Koechlin & Summerfield, 2007; Fuster, 2001; Fuster, Bodner, & Kroger, 2000). However, research on human problem-solving requires a new level of temporal precision to determine frontal-parietal regions' specific roles at different stages of problem-solving processes.

Human problem-solving, such as observed in widely used mental arithmetic task paradigms (Tschentscher & Hauk, 2014; Arsalidou & Taylor, 2011; Grabner et al., 2009; Stocco & Anderson, 2008), involves a temporal sequence of cognitive operations within the first second after task onset: the stimulus encoding, the structuring of solution steps, as well as their execution. fMRI studies have emphasized the mutual activation of a frontal-parietal network in response to a broad range of task demands in numerical (Tschentscher & Hauk, 2014; Arsalidou & Taylor, 2011) and nonnumerical (Cole et al., 2013; Duncan, 2010) domains. However, the few EEG and MEG studies that have tracked the time course of brain activation in these regions suggest differential brain dynamics in frontal and parietal cortices in the early phases of problem-solving. For example, frontal cortex showed effects of executive control before parietal cortex in a task-switching paradigm using dipole-modeling of ERP data (Brass, Ullsperger, Knoesche, von Cramon, & Phillips, 2005). Importantly, a recent EEG–MEG study using distributed source modeling revealed that right frontal cortex activates before parietal cortex when complex arithmetic problems were contrasted with easy ones (Tschentscher & Hauk, 2016). Although this is evidence for a role of frontal cortex at an early stage of the problem-solving process, this study could not clarify whether frontal cortex at this stage (a) is involved in the specific process of structuring the sequence of solution steps or (b) reflects more general demands of task encoding, such as predicted by arithmetic problem size, which has been shown to strongly influence RTs (cf. Tschentscher

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& Hauk, 2015). Furthermore, the previous study unexpectedly found early frontal activation to be right-lateralized. This requires replication. Here, we will characterize the role of right-frontal cortex in arithmetic problem-solving in more detail.

Several authors have highlighted the impact of frontal cortex on the temporal integration of multiple cognitive steps based on fMRI and monkey electrophysiology research (Koechlin & Summerfield, 2007; Fuster, 2001). Similar to its relevance in sequencing of complex movements (cf. Dippel & Beste, 2015; Shima, Isoda, Mushiake, & Tanji, 2007), frontal cortex may also support the early organization of multiple task requirements in symbolic problem-solving. This hypothesis has been investigated in previous fMRI research, suggesting the role of frontal areas in hierarchical structural building within domains of language, musical syntax, and arithmetic (for reviews, see Jeon, 2014; Makuuchi, Bahlmann, & Friederici, 2012; Menon, 2010). In contrast, parietal areas have been frequently associated with aspects of numerical encoding and number manipulation, as shown by a broad range of fMRI studies (Dehaene, Piazza, Pinel, & Cohen, 2003). In particular, intraparietal sulcus regions may be sensitive to number size effects (e.g., two-digit vs. one-digit numbers) in arithmetic problem-solving paradigms (cf. Arsalidou & Taylor, 2011). However, evidence is scarce on the time-resolved neural dynamics within frontal and parietal cortex across stages of an arithmetic process.

We here investigated the role of frontal and parietal cortex during early phases of problem-solving by analyzing whole-brain source reconstructions of combined EEG–MEG measures. Our arithmetic problem-solving paradigm allowed us to dissociate early task encoding demands as a function of problem size from the specific demands of early solution step structuring. We manipulated the task encoding demands by defining two levels of task complexity based on the number size of operands (e.g., "3 × 7" vs. "3 × 24").

To assess early solution structuring processes, we manipulated the demands of performing multiple solution steps independently from general executive demands. Both smaller and larger numerical problems (i.e., the easy and complex conditions) had to be solved in two different ways: by basic multiplication of two numbers as well as by using an arithmetic sequence rule that required participants to perform at least two solution steps even in the case of small numbers ("first add the two digits and then multiply the sum with the smaller digit"). Hence, our experimental design consisted of the four conditions "Easy Multiplication," "Complex Multiplication," "Easy Sequence," and "Complex Sequence."

Only the "Easy Multiplication" condition could be solved by direct memory retrieval of solutions, whereas the "Complex Multiplication" condition required at least two solution steps because of the large number size of the problems. Using trial-by-trial strategy ratings, previous studies showed that multiplication problems involving only small one-digit numbers most likely elicit direct memory retrieval of solutions, whereas multiplication problems involving a combination of one-digit and two-digit numbers require the performance of at least two solution steps (Tschentscher & Hauk, 2014, 2015). In the sequence conditions, participants solved tasks consisting of the same problem sizes as in the multiplication conditions but had to apply an initial solution structuring step irrespective of the numerical size of problems (see Table 1). Because of this rule, the "Easy Sequence" condition required two solution steps despite the small number size of the problems, and the "Complex Sequence" condition required at least two solution steps because of the large number size of the problems as well as the introduced rule.

Table 1. Features of the Four Arithmetic Task Conditions

Conditions	*Features*	*Example*
Easy Multiplication	1/1 digit task	3 × 7
	number range 2–5/5–9	
Complex Multiplication	1/2 digit task	2 × 34
	number range 2–5/21–40	
Easy Sequence [add digits] × smaller digit	1/1 digit tasks	(3 + 4) × 3
	number range 2–7	
	numbers adding up to 5–9	
Complex Sequence [add digits] × smaller digit	1/2 digit task	(2 + 32) × 2
	number range 2–5/21–40	
	numbers adding up to 21–40	

The two rule types "Multiplication" and "Sequence" were matched with respect to the number size of the result on each complexity level (red and green highlights). These examples indicate the required calculation steps, not the presented stimulus sequence (please see Figure 2 for information on the presented stimulus sequence).

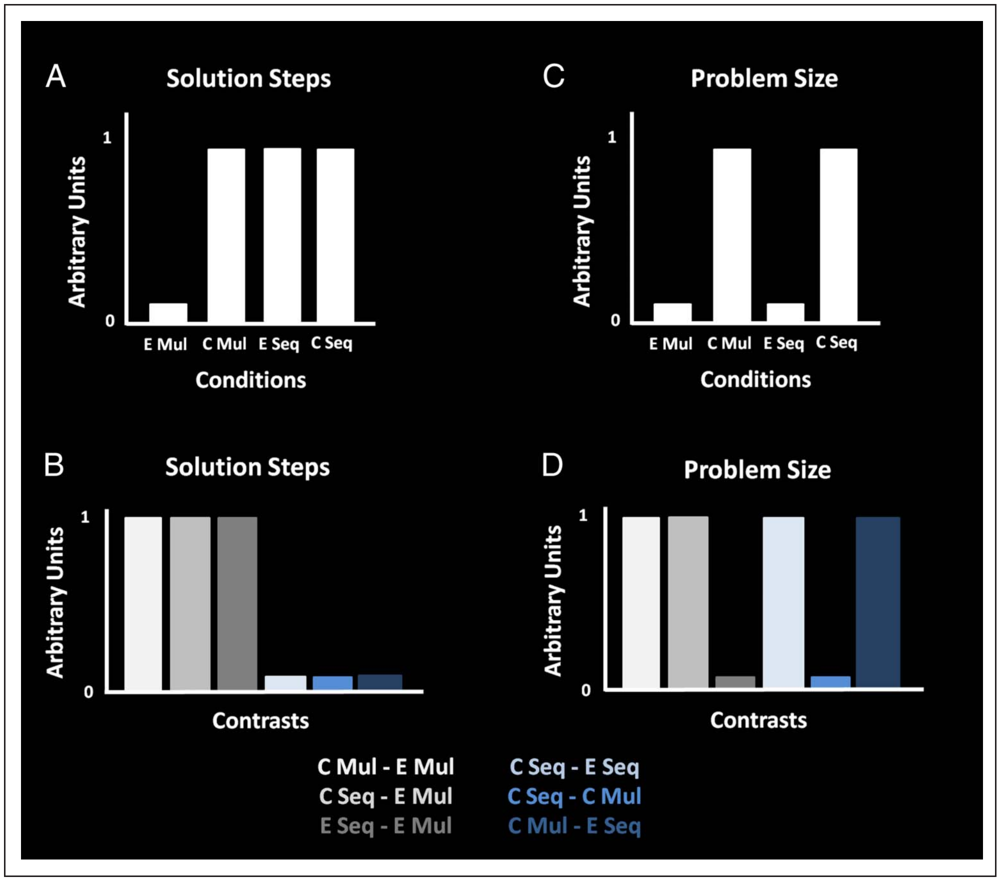

Figure 1. Predictions for frontal cortex activation during early task processing phases for the solution step demand account (A and B) and the task encoding demand account (C and D), respectively. Specific contrasts of interest are based on the four conditions: Easy Multiplication (E Mul), Complex Multiplication (C Mul), Easy Sequence (E Seq), and Complex Sequence (C Seq). (A) Prediction for neural activation patterns as a function of solution steps. (B) Neural activation patterns for contrasts as a function of solution steps. (C) Prediction for neural activation patterns as a function of problem size. (D) Neural activation patterns for contrasts as a function of problem size.

We compared two accounts for early frontal cortex functions: Are neural effects in frontal cortex during early phases of problem-solving explained by task encoding demands, that is, as a function of problem size? Or are they rather predicted by demands of multistep solution structuring, that is, by neural differences between the easy multiplication condition and all other conditions that required at least two solution steps? Neural activations in frontal cortices were analyzed regarding these two competing accounts (Figure 1). If frontal cortex was specifically involved in early preparation of multiple solution steps, then neural activations should be higher for all conditions that require at least two solution steps (Figure 1A), resulting in relatively stronger activation for these conditions when contrasted with easy multiplication, that is, the only condition that can be solved by direct memory retrieval (Figure 1B). If frontal cortex instead reflected early task encoding demands, then the pattern of neural activity in frontal cortex should be predicted by problem size across conditions and contrasts (Figure 1C and D).

METHODS

Participants

EEG and MEG data from 23 healthy participants (18 women) were analyzed (mean age = 27.5, *SD* = 3.4). They were all right-handed, as confirmed by the 10-item version of the Edinburgh Handedness Inventory (Oldfield, 1971), and had normal or corrected-to-normal vision. They reported no history of neurological or psychiatric disorders. Before their selection, all participants indicated in an email questionnaire that they could solve the type of arithmetic problems employed in this study. Participants' IQ was assessed at the day of testing by using the Culture Fair Test Scale 2 (Cattell & Cattell, 1960). Participants received about £40 for their participation, and ethical approval was obtained from the Cambridge Local Research Ethics Committee.

Stimuli

The tasks for the easy and complex "Multiplication" conditions were selected in accordance with the multiplication tasks in previous fMRI and EEG–MEG studies (Tschentscher & Hauk, 2016; for details on number ranges, see Table 1). To control for solution step structuring demands independently of task encoding demands, two "Sequence" conditions were defined, asking participants to first add the two digits and then to multiply the sum by the smaller of the two digits. The two rule types "Multiplication" and "Sequence" were matched with respect to the number size of the result on each complexity level (Table 1, red and green highlights). Each of the four conditions ("Easy Multiplication," "Complex Multiplication," "Easy Sequence," and "Complex Sequence") consisted of 60 tasks. Tasks were carefully matched according to the following criteria: An equal amount of problems containing two even numbers, two odd numbers, as well as odd/even and even/odd number combinations were chosen. The maximum height of stimuli was 15 mm. Stimuli were presented within a visual angle of less than 4° in Calibri font.

Procedure

Each arithmetic problem consisted of two numbers that were sequentially presented, preceded by a cue indicating either the "Multiplication" or "Sequence" rule (Figure 2). In the easy and complex "Sequence" conditions, a two-step solution process had to be performed: First the two numbers had to be added, and then the sum had to be multiplied by the smaller of the two presented numbers. For example, in the easy condition examples in Table 1, participants saw the numbers 3 and 4 in the "Sequence" condition. Participants knew that they had to add the two numbers first, yielding 7, and then multiply the sum by the smaller of the presented numbers, that is, 3 × 7. In the easy and complex "Multiplication" conditions, participants just multiplied the two presented numbers, that is, 3 × 7 in the easy condition examples in Table 1, as soon as the second number appeared on screen. Thus, the "Multiplication" and "Sequence" rules were matched with respect to the number size of the result. However, a preceding addition step was required in the "Sequence" condition to force a multistep solution process even in the case of numerically small problems.

For complex conditions containing a one-digit number in combination with a two-digit number, the two-digit number was always presented second in the order of the trial sequence. This was to ensure that no effects of anticipated task complexity due to number size emerged before the critical calculation interval. Counterbalanced across all runs and conditions, cues consisted either of a string of symbols ("◊◊x◊" or "◊+x◊") or a verbal indication ("1step" or "2step"). Different cue types were used to allow further analyses on task encoding, which are not reported here. Both cue types were matched in visual length on screen, using "◊" as fillers in the case of symbols. In a self-paced calculation interval, participants were told to press a button as soon as they knew the answer, which triggered the onset of a two-alternative forced choice result display. The result display remained on screen for 750 msec only, thus discouraging participants to "preemptively" press the button before they finished calculating. A similar procedure has been used in previous arithmetic task paradigms (Tschentscher & Hauk, 2015; Lemaire & Arnaud, 2008), where it was proven to provide reliable RT measures while having the advantage that the answer options are still unknown during the calculation phase, as opposed to a classical two-alternative forced choice paradigm (Tschentscher & Hauk, 2015). Participants had to confirm the correct solution that was presented together with a distractor. For problems

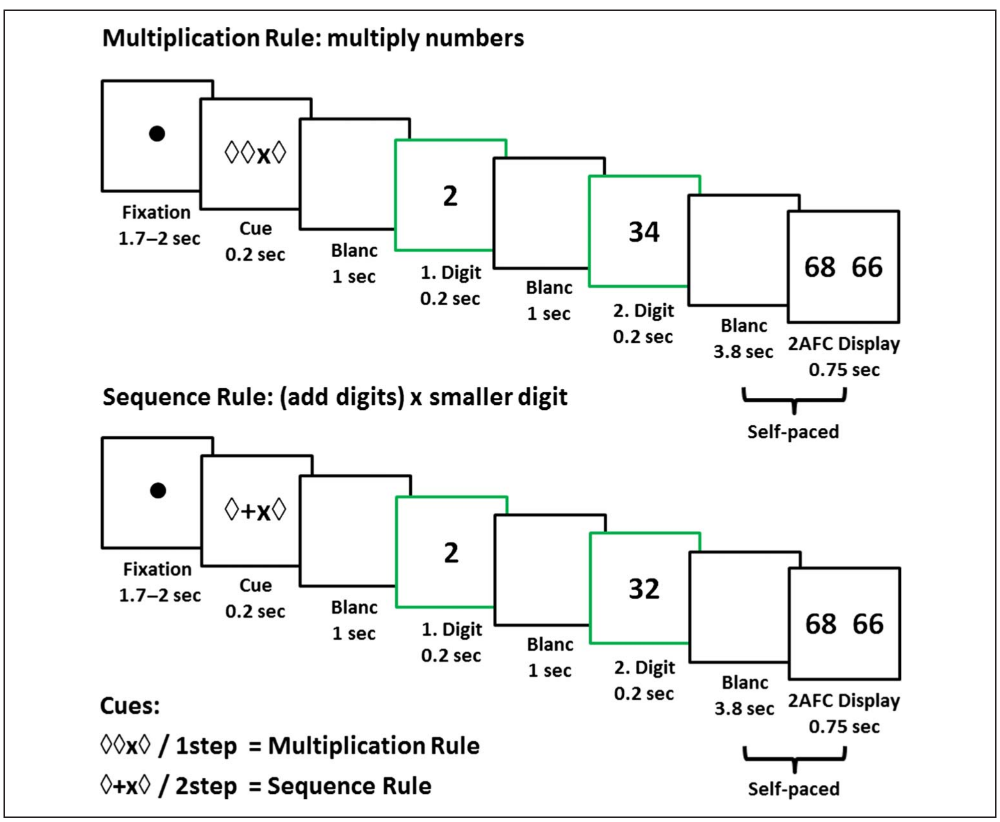

Figure 2. Examples of trial sequences for each rule type. Two numbers were presented in sequence (green rectangles) and had to be combined according to two different rules (top and bottom) to yield the result. Both rules were matched with respect to the number size of the result (68 in these examples). The relative sizes of stimuli and fixation dot have been changed for visualization purposes.

containing two one-digit numbers (easy conditions), the distractor was within the range of ±2 of the correct solution. For complex problems consisting of combinations of one-digit and two-digit numbers, 50% of the distractors were either within a range of ±2 of the correct solution (e.g., 56 and 54) or ±10 of the correct solution (e.g., 42 and 52) each. Exceptions were made for trials including the number five: Distractors in those trials were within a range of ±5 of the correct solution. The position of the correct solution on the screen was counterbalanced across all trials within each condition. The interstimulus interval was jittered between 1.7 and 2 sec. The experiment was divided into eight blocks. Each block contained an equal amount of tasks from each of the four conditions. The duration of each block was approximately 7 min. Fifteen practice tasks were presented at the beginning of the EEG–MEG session. Fluid intelligence measures from the Culture Fair Intelligence Test (Cattell & Cattell, 1960) were obtained after the EEG–MEG session.

EEG–MEG Data Acquisition

The continuously recorded MEG (306-channel Elekta Neuromag Vectorview system, Stockholm, Sweden) and EEG (70 electrodes) were digitally sampled at 1 kHz. The position of five head position indicator coils, attached to the EEG cap, were digitized with a 3Space Isotrak II System (Fastrak Polhemus, Inc., Colchester, VA) to determine the head position within the MEG helmet. Three anatomical landmark points (nasion and preauricular points) as well as 50–100 additional randomly distributed points (head shape) were digitized for an accurate coregistration with MRI data. The EOG was recorded bipolarly through electrodes placed above and below the left eye (vertical EOG) and at the outer canthi (horizontal EOG). Artifacts likely to be produced by sources distant to the sensor array were removed by means of the signal space separation method, which is implemented in the Neuromag "Maxfilter" software (Taulu & Kajola, 2005). The spatiotemporal variant of Maxfilter, as well as the movement compensation, was applied. EEG and MEG data were inspected visually, and interpolation of EEG channels was applied. Eye movement artifacts in EEG and MEG data were removed by an independent component analysis, run in MNE Python software 0.8 (Gramfort et al., 2013). This was applied to continuous data for magnetometers, gradiometers, and EEG scalp potentials separately to identify and subsequently remove components whose time courses correlated with eye movement artifacts.

Data were offline band-pass filtered between 0.1 and 40 Hz before averaging. For each of the four conditions, epochs from −100 to 800 msec after onset of the second number (Figure 2) were averaged by using the MNE Python software 0.8. Trials were rejected during averaging when the maximum–minimum amplitudes exceeded the following thresholds in the averaged interval: 120 μV in EEG, 4000 fT in magnetometers, and 4000 fT/cm in gradiometers. EEG data were rereferenced to average reference, and the mean amplitude of the 100 msec baseline interval was subtracted at all time points on each channel.

Source Estimates

Source estimates were derived from combined EEG and MEG data by using the MNE Python software 0.8 package in combination with FreeSurfer (Version 4.3.0; surfer.nmr.mgh.harvard.edu/). A minimum norm estimation (MNE) method (Hauk, 2004; Hämäläinen & Ilmoniemi, 1994) was used that makes minimal a priori assumptions on the distribution of cortical sources. The noise covariance matrices for each data set were computed for baseline intervals of 300-msec duration before the onset of each arithmetic task. The noise covariance matrix is used to combine measurements from different sensor types (magnetometers, gradiometers, and EEG electrodes): All measures are transformed into signal-to-noise ratios ("pre-whitening") to suppress noise in the source estimates. For regularization, the default signal-to-noise ratio was used (SNR = 3). EEG–MEG sensor configurations and MRI images were coregistered based on the matching of about 50–100 digitized points on the scalp surface. High-resolution structural T1-weighted MRI images of each individual participant were used, acquired in a 3-T Tim Trio (Siemens, Erlangen, Germany) scanner at the MRC Cognition and Brain Sciences Unit (UK) with a 3-D MPRAGE sequence, field of view of 256 mm × 240 mm × 160 mm, matrix dimensions of 256 × 240 × 160, 1-mm isotropic resolution, repetition time = 2250 msec, inversion time = 900 msec, echo time = 2.99 msec, flip angle = 9°. The scalp surface of the MRI images was reconstructed by using the automated segmentation algorithms of the FreeSurfer software. By using the traditional method for cortical surface decimation, the original triangulated cortical surface (consisting of several hundred thousand vertices) was down-sampled to a grid with an average distance between vertices of 5 mm, which resulted in approximately 1000 vertices. A boundary element model containing 5120 triangles was created from the inner skull surface for MEG measurements by using a watershed algorithm. For EEG, the boundary element model was created with three layers for scalp, outer skull surface, and inner skull surface. Dipole sources were assumed to be almost perpendicular to the cortical surface, with some variation in the tangential plane (one fifth of the radial dimension). Note that source distribution time courses are unaffected by the choice of EEG reference electrode. This is one of the advantages of source space compared with signal space analysis.

Source estimates were computed for each participant and condition. The results for each individual data set were morphed to the average brain across all participants. Time windows of interest for statistical analyses on EEG–MEG source estimates were defined based on the peaks in mean EEG–MEG source activity across all vertices and conditions (see Figure 3).

Six contrasts of interest were defined to dissociate aspects of solution step structuring from task encoding demands: “Easy Sequence/Easy Multiplication,” “Complex Sequence/Easy Multiplication,” “Complex Multiplication/Easy Multiplication,” “Complex Sequence/Complex Multiplication,” “Complex Sequence/Easy Sequence,” “Complex Multiplication/Easy Sequence” (see Figure 1). It was predicted that contrasts between “Easy Multiplication” and all other conditions would reflect differences between direct memory retrieval and a multistep solution process. In contrast to this, it was predicted that the “Easy Sequence” and “Complex Sequence” conditions, as well as the “Complex Multiplication” and the “Easy Sequence” conditions, would differ in task encoding demands only. Task endcoding demands were predicted based on problem size (two-digit vs. one-digit numbers; see Figure 1). For each of the six contrasts, permutation-based whole-brain cluster-level statistics were applied to the averaged MNE source amplitudes within each time window of interest. A nonparametric cluster-level *t* test for spatiotemporal data was used (Maris & Oostenveld, 2007). The permutation test corrected for multiple comparisons across all vertices of whole-brain source estimates within each of the a priori defined time windows.

RESULTS

Behavior

Mean RTs were used to restrict the time window for EEG–MEG analyses (Easy Multiplication = 895 msec, *SD* = 375; Complex Multiplication = 1540 msec, *SD* = 519; Easy Sequence = 1853 msec, *SD* = 507; Complex Sequence = 2306 msec, *SD* = 609). Because the shortest behavioral responses (for the “Easy Multiplication” condition) were around 500 msec, time windows of interest for evoked EEG–MEG analyses were only defined up to 450 msec poststimulus onset. Analyses on neural differences between conditions beyond this time point would not have been meaningful. Furthermore, analyses were performed on time windows up to 450 msec only, because our main interest was to assess the role of frontal cortex in early phases of strategy selection around 300 msec (cf. Tschentscher & Hauk, 2016).

As expected, RTs reflected a combination of solution step and problem size demands. An ANOVA with the factors Problem Size (easy vs. complex conditions) and Rule Type (multiplication vs. sequence rule) revealed a main effect of Problem Size ($F(1, 22) = 105.92$, $p < .000$), a main effect of Rule Type ($F(1, 22) = 324.54$, $p < .000$), as well as a significant Problem Size × Rule Type interaction ($F(1, 22) = 12.85$, $p = .002$). The error rate for all conditions was low (mean percent across participants = 8.5, *SD* percent across participants = 6.5). Error trials were removed from RT analyses as well as EEG–MEG analyses.

Participants' IQ scores (mean = 128, *SD* = 16) did not show any significant correlations with RTs or error rates. This was not surprising: Because of the prescreening of participants with regard to their mental calculation skills, a relatively homogenous performance group was tested, with above average IQ scores.

EEG–MEG

Three time windows for evoked analyses were defined based on mean signal intensity across all vertices in source space for the average across all four task conditions (Figure 3): 100–150 msec, 150–300 msec, and 300–450 msec. The two main time windows of interest were the 150–300 msec and 300–450 msec windows. These time windows were chosen based on previous EEG–MEG research that reported specific effects of arithmetic strategies between 200 and 400 msec (Tschentscher & Hauk, 2016), as well as previous ERP studies that observed arithmetic strategy effects between 300 and

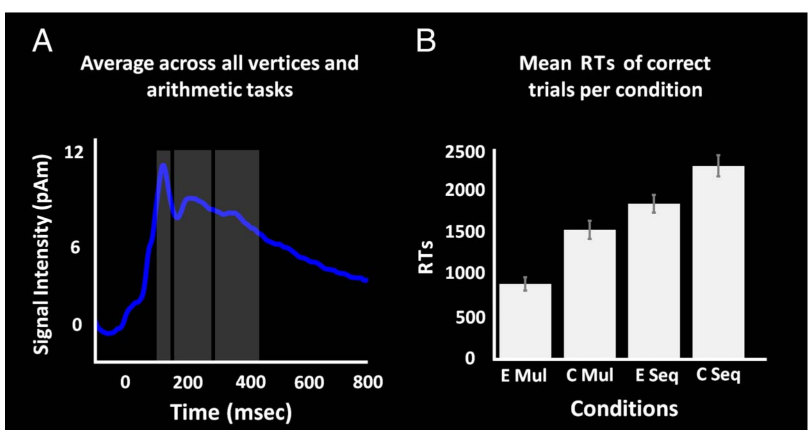

Figure 3. (A) Overall activation time courses in evoked source estimates averaged across all vertices and task conditions. Gray areas indicate the time windows used for statistical analyses. (B) Mean RTs of all correct trials for the four conditions: Easy Multiplication (E Mul), Complex Multiplication (C Mul), Easy Sequence (E Seq), and Complex Sequence (C Seq). Error bars indicate *SEM*.

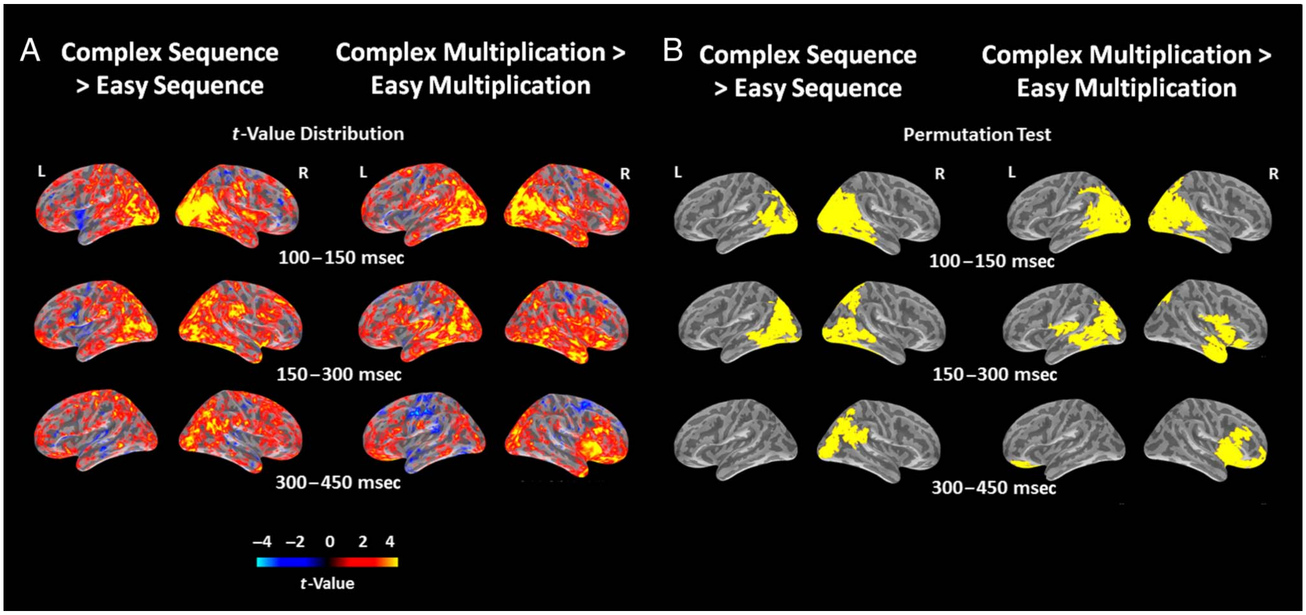

Figure 4. (A) EEG–MEG minimum norm *t* value distributions. (B) Significant clusters of the corresponding permutation tests. Early frontal effects between 300 and 450 msec only occurred for the contrast "Complex Multiplication–Easy Multiplication." No such effect was observed for the contrast of conditions "Complex Sequence–Easy Sequence" that differed in problem size but not in the number of executed substeps.

600 msec (Nunez-Pena, Cortinas, & Escera, 2006; El Yagoubi, Lemaire, & Besson, 2003; Iguchi & Hashimoto, 2000). The short 100–150 msec time window was included in the analyses because of its clear peak in the overall activation time course, as predicted in terms of an early visually evoked response based on previous ERP studies on numerical encoding (Szűcs & Csépe, 2004; Dehaene, 1996).

To describe the general time course of brain activation at the whole-brain level, source estimates of combined EEG–MEG signal were first analyzed in each of the four time windows for the two main contrasts of "Complex Sequence–Easy Sequence" and "Complex Multiplication–Easy Multiplication" (Figure 4). Early right frontal activations were observed in EEG–MEG minimum norm *t* value distributions and permutation tests for the contrast "Complex Multiplication–Easy Multiplication" in the 300–450 msec time window (Figure 4A and B, right). No such frontal effects were observed for the contrast "Complex Sequence–Easy Sequence" in any of the analyzed time windows (Figure 4A and B, left).

Early differential evoked effects for the contrasts of "Complex Sequence–Easy Sequence" and "Complex Multiplication–Easy Multiplication" were localized around 100 msec in occipital and parietal regions, suggesting that these effects reflected differences in task endcoding demands, depending on problem size (one-digit vs. two-digit numbers) between the easy and complex conditions. These demands were also reflected in occipital and temporal regions in the time window between 150 and 300 msec for both contrasts. Contrasts between conditions that did not differ in task encoding demands because of their equal problem size ranges (e.g., "Complex Multiplication–Complex Sequence" and "Easy Multiplication–Easy Sequence") did not show any of those early parietal and temporal effects.

In a next step, we focused on the time window of 300–450 msec since it revealed differential right frontal effects for the two main contrasts "Complex Sequence–Easy Sequence" and "Complex Multiplication–Easy Multiplication" (Figure 4). Furthermore, specific right frontal effects in EEG–MEG sources around 300 msec have been observed previously for self-reported multistep solution strategies in contrast to direct memory retrieval strategies in an arithmetic task paradigm (cf. Tschentscher & Hauk, 2016). Early frontal effects in the 300–450 msec window were assessed for each of the six contrasts of interest. These contrasts were evaluated regarding the two competing accounts on frontal cortex' functions (Figure 1), either predicting the specific involvement of frontal cortex in solution step structuring demands (Figure 1B) or rather in early task encoding demands as a function of problem size (Figure 1D).

Significant clusters in whole-brain permutation tests provided evidence for the specific involvement of right frontal cortex in early solution step structuring processes: Right frontal effects only occurred for contrasts of conditions differing in the number of required solution steps, that is, between "Easy Multiplication," which can be solved by direct memory retrieval, and "Complex Multiplication," "Easy Sequence," as well as "Complex Sequence" (Figure 5A). Contrasts between conditions that differed in task encoding demands, but not in solution step demands, did not show any early engagement of frontal cortices (Figure 5B). For example, the contrast "Complex Multiplication–Easy Sequence" did not reveal any differential effects in frontal cortex because both conditions that constituted this contrast required multiple substeps. This is in line with previous behavioral and EEG–MEG research, showing that multiplication tasks of the same number range as in the "Complex Multiplication" condition were solved by multistep solution strategies, whereas tasks used for the "Easy Multiplication" condition could be solved by direct memory retrieval, as assessed based on strategy self-reports of participants (Tschentscher & Hauk, 2015, 2016). The absence of early frontal effects for contrasts of conditions that both required multiple solution steps was also shown with regard to the contrast "Complex Multiplication–Complex Sequence" (Figure 5B). Furthermore, the underlying conditions did not differ in early visual encoding demands because their tasks were matched in number range. Thus, they neither caused parietal or temporal effects during early number encoding time windows nor frontal effects during later phases of strategy execution. Overall, this suggests that early frontal effects occurred because of differences in multistep solution demands, whereas differences in task encoding demands between conditions with an equal numbers of substeps did not evoke any early frontal effects.

We also explored the impact of RTs, that is, general task demands, on the observed effects. It is important to note that all of our conditions significantly differed in RTs. However, although contrasts including "Easy Multiplication" differed in RTs and in required substeps, conditions of the other contrasts (e.g., "Complex Sequence–Easy Sequence" and "Complex Multiplication–Complex Sequence") only showed substantial differences in RTs but not in required substeps. Hence, if RTs would predict early right frontal effects, then such effects should be present for all contrasts of conditions that differed in RTs. However, we could show that right frontal effects only emerged for contrasts of conditions that, in addition to

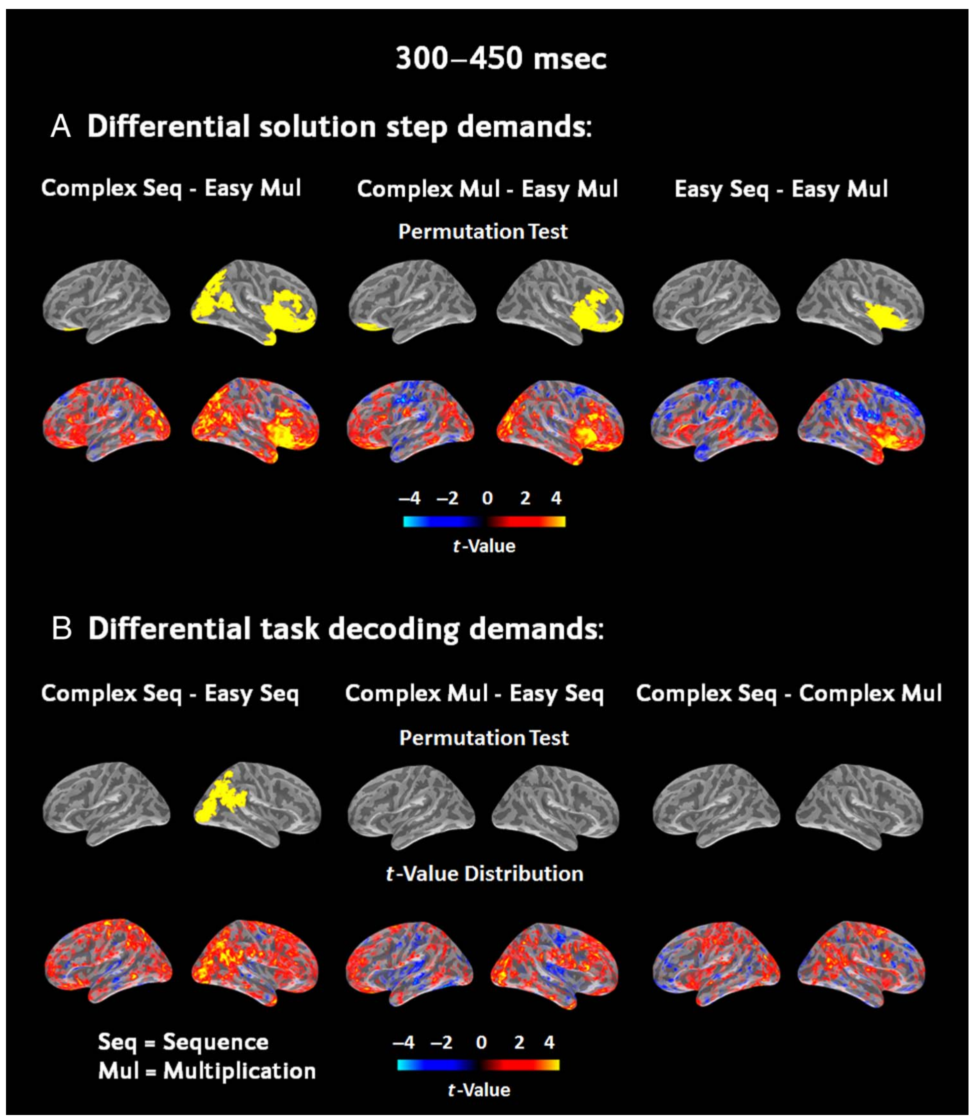

Figure 5. EEG–MEG minimum norm source estimates of task phases between 300 and 450 msec. (A) *t* Value distributions and significant clusters of permutation tests for contrasts of conditions that required multiple solution steps versus direct memory retrieval. (B) *t* Value distributions and significant clusters of permutation tests for contrasts of conditions that differed in task encoding demands as a function of problem size. The contrast "Complex Sequence–Complex Multiplication" neither differs in solution steps nor in task encoding demands. Frontal cortices only showed significant effects of solution structuring demands but not of task encoding demands.

their differences in RTs, also differed in the number of required substeps.

DISCUSSION

We assessed the spatiotemporal dynamics of frontal-parietal cortex across stages of problem-solving using an arithmetic task paradigm. Although metabolic neuroimaging research has robustly demonstrated activation in these brain regions related to executive control during a broad range of demanding tasks (Cole et al., 2013; Duncan & Owen, 2000), the temporal dynamics within this network are largely unknown. Time-resolved measures from EEG–MEG allow the temporal dissociation of early and late problem-solving phases, such as the early structuring as well as later execution of solution steps. A previous study found early right frontal effects around 300 msec for contrasts between self-reported multistep procedural arithmetic strategies and direct memory retrieval strategies (Tschentscher & Hauk, 2016). Here, we aimed to assess the role of early right frontal cortex activation in more detail. We could replicate early right-lateralized frontal activation in a similar paradigm, and importantly, we could show that these effects are specifically associated with the structuring of multiple solution steps as opposed to the demands of task encoding.

Using combined EEG–MEG source analyses, we analyzed frontal cortex's role in early phases of strategy selection in an arithmetic task paradigm that dissociated the early demands of task encoding from the demands of structuring multiple solution steps. Problem size was taken as predictor for task encoding demands, that is, the difference between multiplication problems involving two one-digit numbers and problems involving a combination of one-digit and two-digit numbers. The number of required solution steps was controlled by comparing basic multiplication with an arithmetic sequence rule that required at least two solution steps independent of problem size.

We observed differential effects because of demands of task encoding and solution step structuring within the first 450 msec of problem-solving: Frontal cortex reflected earliest demands in solution step structuring around 300 msec poststimulus. Most importantly, we could show that early right frontal activation around 300 msec occurred specifically as a function of required solution steps. Hence, our results speak for the specific role of right frontal cortex in early structuring of multiple task steps in time windows around 300 msec.

In contrast, parietal effects occurred solely as a function of problem size in time windows between 100 and 300 msec, that is, they reflected early task encoding demands. No parietal effects were observed for conditions that involved problems within the same number range, and no parietal effects were observed in later time windows as a function of solution step demands. In line with the localization of our parietal effects, evidence from a broad range of previous fMRI studies suggests that especially the intraparietal sulcus and posterior parietal lobule are activated whenever numbers of different sizes are decoded as well as manipulated (Arsalidou & Taylor, 2011; Dehaene et al., 2003).

Thus, earliest effects related to the sequencing of the problem-solving process (rather than stimulus encoding) occurred in right frontal cortices around 300 msec (cf. Tschentscher & Hauk, 2016). A point of reference for earliest arithmetic calculation processes is also provided by previous ERP literature. For example, El Yagoubi et al. (2003) found that more difficult arithmetic strategies elicited effects from 300 to 600 msec after the stimulus, and a positive slow potential from 400 msec onwards has been observed related to multistep mental arithmetic calculation in contrast to counting and direct memory retrieval strategies (Nunez-Pena et al., 2006; Iguchi & Hashimoto, 2000), suggesting that this time frame corresponds to a central stage in strategy preparation and execution.

Frontal Cortex's Specific Role in Early Structuring of Multiple Solution Steps

Our specific early right frontal effects replicate previous EEG–MEG results (Tschentscher & Hauk, 2016), and they are in line with the neuroanatomical correlates from previous metabolic neuroimaging studies suggesting frontal cortex's involvement in the control and coordination of a multistage cognitive process (Fuster, 2001; Damasio, Everitt, & Bishop, 1996; Chao & Knight, 1995; Goldman-Rakic, 1995), as well as in the building of hierarchical structures (for reviews, see Jeon, 2014; Makuuchi et al., 2012; Menon, 2010). The limited spatial resolution of EEG–MEG measurements does not allow a precise localization of our effects within frontal cortex. However, our results are consistent with previous claims that lateral frontal cortex may support the temporal integration of multiple task requirements across stages of problem-solving (Koechlin & Summerfield, 2007; Koechlin, Ody, & Kouneiher, 2003). We here provide first evidence that this process occurs during early time windows of problem-solving around 300 msec.

Furthermore, the localization of early solution structuring effects in lateral and posterior frontal cortex fits into the theoretical framework of a posterior-to-anterior gradient of cognitive control (Koechlin & Summerfield, 2007): Posterior frontal cortex has been associated with aspects of contextual control, that is, control of information in a particular task context (cf. Koechlin & Jubault, 2006). In contrast, anterior frontal cortex has been associated with control of episodic memories and premotor regions with sensory control. This may suggest that similar regions are involved in the early structuring of multiple solution steps in the current study, as previously observed to be activated for aspects of contextual task control.

The Lateralization of Early Frontal Effects

Most previous fMRI evidence on the neural correlates of arithmetic problem-solving or general executive control suggests bilateral frontal cortex involvement (Tschentscher & Hauk, 2014; Fedorenko, Duncan, & Kanwisher, 2013; Arsalidou & Taylor, 2011; Grabner et al., 2009). It may therefore be a surprise that we observed right lateralization of early frontal effects in our study. However, our results are in line with findings from a recent study using combined EEG–MEG source reconstructions in a similar arithmetic paradigm (Tschentscher & Hauk, 2016). This study also observed earliest effects of arithmetic strategy selection in right frontal cortex around 300 msec. The current EEG–MEG results further support the view that right frontal cortex primarily engages in the initial structuring of multiple solution steps in early task phases around 300 msec.

Interestingly, it has been suggested that processes of hierarchical structure building in frontal cortex might be lateralized depending on the domain of cognition (for a review, see Jeon, 2014): Aspects of movement coordination and musical syntax processing primarily showed early right frontal activations, in line with effects of the current study (Dippel & Beste, 2015; Koelsch, Rohrmeier, Torrecuso, & Jentschke, 2013; Maess, Koelsch, Gunter, & Friederici, 2001). In contrast, the hierarchical organization of grammatical rules in the language domain has been associated with left-hemispheric Boca's regions (Bahlmann, Schubotz, & Friederici, 2008; Friederici, 2004), as well as with early mismatch negativities in EEG that could be localized in left frontal cortex (Pulvermüller & Shtyrov, 2003). We propose that the sequencing of arithmetic solution steps shares more aspects with nonlinguistic tasks and therefore resulted in right-lateralized frontal activation. This can be tested in future EEG–MEG studies, contrasting brain dynamics in different tasks using different stimulus material.

Conclusion

Using an arithmetic problem-solving paradigm, we here provided novel evidence suggesting the specific role of right frontal cortex in the early structuring of multiple solution steps around 300 msec. We propose that frontal cortex subserves domain-general aspects of problem-solving, such as the structuring of multiple solution steps in a specific time interval around 300 msec. In contrast to this, early parietal effects between 100 and 300 msec occurred as a function of problem size and speak for parietal cortex's role in domain-specific processes of early numerical encoding. Our results demonstrate that EEG and MEG have the potential to reveal the interplay between domain-general regions in the frontal lobes and task-specific networks across the brain in more detail. This, for example, provides the basis for future studies using time-resolved brain connectivity measures.

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