

Can the interference effect in multiplication fact retrieval be modulated by an arithmetic training? An fMRI study

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ABSTRACT

Single-digit multiplications are thought to be associated with different levels of interference because they show different degrees of feature overlap (i.e., digits) with previously learnt problems. Recent behavioral and neuroimaging studies provided evidence for this interference effect and showed that individual differences in arithmetic fact retrieval are related to differences in sensitivity to interference (STI). The present study investigated whether and to what extent competence-related differences in STI and its neurophysiological correlates can be modulated by a multiplication facts training.

Participants were 23 adults with high and 23 adults with low arithmetic competencies who underwent a five-day multiplication facts training in which they intensively practiced sets of low- and high-interfering multiplication problems. In a functional magnetic resonance imaging (fMRI) test session after the training, participants worked on a multiplication verification task that comprised trained and untrained problems.

Analyses of the behavioral data revealed an interference effect only in the low competence group, which could be reduced but not resolved by training. On the neural level, competence-related differences in the interference effect were observed in the left supramarginal gyrus (SMG), showing activation differences between low- and high-interfering problems only in the low competent group. These findings support the idea that individuals' low arithmetic skills are related to the development of insufficient memory representations because of STI. Further, our results indicate that a short training by drill (i.e., learning associations between operands and solutions) was not fully effective to resolve existing interference effects in arithmetic fact knowledge.

1. Introduction

Retrieving the correct answer to arithmetic problems, such as 3×4 , provides the basis to process complex calculations more efficiently (Kilpatrick et al., 2001). Arithmetic facts, such as single-digit multiplication problems (Roussel et al., 2002), are thought to be stored in an arithmetic facts network in semantic memory (Ashcraft, 1987; Campbell, 1995; McCloskey and Lindemann, 1992; Verguts and Fias, 2005). However, despite extensive practice in school, there are large individual differences in the development and acquisition of arithmetic facts (De Visscher et al., 2016; Dowker, 2005, 2015; Geary et al., 2012; Jordan et al., 2003). Recent findings (De Visscher and Noël, 2013) suggest that individual differences in multiplication fact knowledge are partly due to

differences in sensitivity to interference (STI) during the acquisition of multiplication problems. Individuals with higher (compared to lower) sensitivity to interference would experience more proactive interference (from previously learned problems) during arithmetic fact learning, which results in poorer memory representations and lower arithmetic competencies. Evidence for this assumption was found not only on behavioral (De Visscher and Noël, 2014b) but also on neural level (De Visscher et al., 2018). However, little is known yet about the malleability of the competence-related differences in arithmetic fact knowledge. Would an intensive practice of presumably high-interfering multiplication problems (1) reduce the STI effect and consequently (2) would it reduce competence-related differences in arithmetic fact retrieval at both the behavioral and the neural level? This question is

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addressed in the present training study.

De Visscher and Noël (2014a) have shown that performance in single-digit multiplication problems is influenced by similarities (i.e., the digit composition of the problem and its answer) between problems. According to their STI hypothesis, arithmetic facts learning (multiplications) suffers from proactive interference because many multiplications share the same elements (i.e., the digits from 0 to 9) (based on the model of Oberauer and Lange, 2008). More precisely, when children learn arithmetic facts, they must create a reliable bond between a problem (e.g., 6×8) and its answer (e.g., 48), both sharing similar digits with previously learnt problems. For instance, $6 \times 7 = 42$ and $6 \times 8 = 48$ have one operand (6) and the decade (40) of the answer in common. Due to this representational overlap, previously encoded information makes it difficult to store new related associations over the course of development and learning. The more elements (i.e., digit associations) a multiplication shares with previously learnt problems, the more interference must be resolved and the more difficult it is to memorize the problem-answer association and retrieve it from memory.

Based on this assumption, De Visscher and Noël (2014a) developed a measure of interference weight for each single-digit multiplication. This interference parameter reflects the digits' overlap between the previously learned multiplications and the current one, according to the learning order from table 2 to table 9. In a series of experiments (De Visscher et al., 2016; De Visscher and Noël, 2014b), it has been shown that this parameter was able to predict performance (i.e., response latency) on multiplication problem solving. More precisely, these studies revealed that the mean response latency for solving a multiplication correctly increases as the interference weight of the problem increases. This linear relationship was found for third and fifth graders as well as undergraduate students. De Visscher and Noël (2014a) concluded that highly interfering problems are not stored in memory and therefore time-consuming computing strategies must be used to solve these problems. Moreover, and most importantly, it has been shown that people with poor arithmetic facts competencies are particularly sensitive to this interference (De Visscher & Noël, 2014a, 2014b). For instance, De Visscher and Noël (2014a) compared data of a single-digit multiplication production task in a 42-year-old woman suffering from dyscalculia to a matched control group and found that the size of the interference parameter effect in this woman was significantly larger than the one in matched control group. Similar results were found in a group of fourth-grade children with low scores in single-digit multiplication and additions fluency tasks. When compared to a gender, age, and class matched control group these children exhibited a higher interference parameter effect (De Visscher and Noël, 2014b). These results support the hypothesis that hypersensitivity to interference in individuals with low arithmetic competencies disturbs the storage and subsequently the retrieval of multiplication facts (De Visscher and Noël, 2013).

On the neural level, various studies have demonstrated a dissociation between brain networks underlying arithmetic fact retrieval and those brain regions associated with more complex procedural strategies (e.g., for a review, cf. Menon, 2014; for a meta-analysis, cf. Arsalidou and Taylor, 2011). Using functional magnetic resonance imaging (fMRI) in adults, Grabner et al. (2009a) found greater activation of the left angular gyrus (AG) for arithmetic problems (i.e., single-digit additions, subtractions, multiplications and divisions) that were solved by memory retrieval compared to problems for which participants reported procedural strategies (i.e., counting or transformation). The application of procedural strategies, on the other hand, activated a widespread fronto-parietal network (e.g., the left and right insula lobe, the left inferior parietal lobule (IPL), the left and right supplementary motor areas (SMA) and the right inferior frontal gyrus (IFG). These findings indicate that the left angular gyrus mediates arithmetic fact retrieval whereas solving effortful problems by procedural strategies is accompanied by broad fronto-parietal activation.

This interpretation was further corroborated in training studies

showing that an intensive training of arithmetic problems leads to a shift of brain activation from fronto-parietal areas (e.g., the left and right IFG, intraparietal sulcus (IPS) and IPL) to increased activation in the AG (e.g., Delazer et al., 2003; 2005; Grabner et al., 2009a,b; Ischebeck et al., 2006). For instance, Ischebeck et al. (2006) showed that a five day training of complex multiplication problems in adults resulted in a decrease of activation especially in frontal regions (i.e., right SMA and right and left IFG) and an increase in the left AG – a finding that was replicated by Grabner et al. (2009a,b). The authors argued that learning of arithmetic problems reduces the general need for domain-general cognitive processing (e.g., working memory and executive control), which is associated with greater brain activation in fronto-parietal regions (Ischebeck et al., 2006). Increased activation in the left AG, however, was thought to indicate arithmetic fact retrieval from long-term memory, which is less demanding relative to procedural strategies (Hinault and Lemaire, 2016). Specifically, the AG could reflect an automatic mapping of arithmetic problems onto answers stored in long-term memory (e.g., De Visscher et al., 2015; Grabner et al., 2013).

However, the recruitment of brain regions associated with arithmetic problem solving not only changes as function of training and development but is also modulated by individual differences in mathematical competence (e.g., Berteletti et al., 2014; De Smedt et al., 2011; Grabner et al., 2007). For instance, by comparing two groups of young adults, Grabner et al. (2007) found that mathematically more (compared to less) competent participants showed greater activity in the left AG while solving easy (single-digit) and difficult (multi-digit) multiplications. These findings were interpreted as reflecting a stronger reliance on fact retrieval in the individuals with better mathematical competencies.

Importantly, the activation of brain regions associated with multiplication problem solving has also been shown to be modulated by the interference weight of the problem (De Visscher et al., 2015). In an event-related fMRI design, De Visscher et al. (2015) investigated the neural interference effect in healthy adults by comparing low with high interfering multiplication problems. To this end, 20 participants worked on a multiplication verification task. While brain activation in the left AG was found to be greater for low interfering problems, the correct solving of high interfering problems was associated with higher activity in frontal brain regions (e.g., the left and right IFG and the anterior insula lobe). The authors concluded that this activation difference reflects the use of different arithmetic strategies, namely memory retrieval for solving low interfering problems and procedural strategies for solving high interfering ones. In a more recent study, De Visscher et al. (2018) examined whether this neural interference effect is linked to individual differences in multiplication performance. As in their preceding study, they used an fMRI-paradigm that contrasted low and high interfering problems in a multiplication verification task. The sample included 42 healthy students that showed high variability in arithmetic fluency. On the behavioral level, the authors found higher performance for low interfering problems, and larger use of fact retrieval for low interfering problems than for high interfering ones. In addition, De Visscher et al. (2018) observed an interference effect on the neural level. High interfering multiplications were accompanied by greater activation in a wide-spread bilateral fronto-parietal network (i.e., bilateral activation was observed in the superior medial gyrus, posterior-medial frontal cortex, middle frontal gyrus, anterior and middle cingulate cortex, insula lobe, caudate nucleus, IFG and IPS; additionally, right-hemispheric activation was observed in the superior orbital gyrus) typically associated with higher cognitive processing. Most importantly, a relationship between the neural interference effect (high > low interfering problems) and arithmetic fluency was observed in the left IFG, with a higher neural interference effect in this region for low performing individuals. These findings are in line with previous studies associating activation in the left IFG to the resolution of interference (Heidekum et al., 2019; Jonides and Nee, 2006) and shows that activation in this region depends on individual differences in arithmetic fluency (Berteletti et al., 2014).

Altogether these findings shed light on three important facts. First, single-digit multiplications are associated with different levels of interference that affect performance during problem solving. Second, this interference effect modulates activation in specific brain regions (e.g., left AG and IFG). Third and most importantly, the behavioral and neural interference effect is linked to individual differences in arithmetic performance. Consequently, the STI might provide a new answer to the question of why some individuals experience difficulties in arithmetic fact retrieval. This new answer, however, also entails the question of whether the STI effect in individuals with lower arithmetic competencies can be modulated. Thus, the present study aimed to investigate whether and to what extent competence-related differences in sensitivity to interference and its neurophysiological correlates can be modulated by multiplication facts training.

To this end, two groups of healthy adults differing in their arithmetic competencies (low versus high) underwent a five-day multiplication facts training. Over the course of training, participants intensively practiced sets of low- and high-interfering multiplication problems. After the multiplication facts training an fMRI test session was conducted in which participants were presented with trained and untrained problems of low and high interference weight. This paradigm enabled us to investigate the training effect, the interference effect, the group effect, and their interactions. On behavioral level, we expected that participants with low arithmetic competencies would benefit more from the training, reflected by increased accuracy and decreased response times, than the high arithmetic competencies group (Grabner et al., 2009a,b). Based on the discussed literature, we expected to find a higher sensitivity to the interference parameter in the low competencies group (i.e., longer response times for high interfering problems as compared to low interfering problems; De Visscher and Noël, 2014b). Further, we expected that the online multiplications fact training would, at least, reduce the behavioral interference effect.

Based on previous arithmetic training studies in fMRI, we expected greater neural response for trained multiplications in the left AG, on the one hand, and larger wide-spread fronto-parietal activity for untrained problems, on the other hand (e.g., Delazer et al., 2003; 2005; Grabner et al., 2009a,b; Ischebeck et al., 2006). Regarding the interference effect, we expected to find bilateral activation in frontal and parietal regions (e.g., insula, IFG, IPS) for high interfering multiplications and bilateral activation of the inferior parietal lobule for low interfering problems (De Visscher et al., 2015, 2018). We also hypothesized that both effects would be modulated by arithmetic competence. Firstly, we expected to observe a competence-related modulation of the neural training effect in the left AG as observed by Grabner et al. (2009a,b). Secondly, competence-related differences in the neural interference effect in the left IFG were expected (De Visscher et al., 2018). Finally, by comparing trained and untrained problems in the scanner, we expected to observe a reduced neural interference effect in trained problems as compared to untrained problems.

2. Method

2.1. Participants

Sixty-one German-speaking students participated in the current study. All participants were selected from a pool of 425 adults (271 females; age: $M = 23$, $SD = 5.6$) of which various competencies and personality traits were assessed. For the current study, 61 participants with low and high arithmetic competencies were recruited (selection procedure described in section 2.2.). Due to missing data ($N = 12$), technical problems ($N = 1$) and other exclusion criteria (i.e., left-handedness and non-German-speaking; $N = 2$) the final sample size comprised 46 healthy young adults. This sample consisted of participants with low ($N = 23$; 18 females) and high ($N = 23$; 10 females) arithmetic competencies. The age of participants with low arithmetic competencies ranged from 19 to 32 years ($M = 23$; $SD = 3.2$) and the age of those with high arithmetic competencies ranged from 21 to 35 years ($M = 24$; $SD =$

3.6). Groups did not differ in age ($t(44) = -1.15$, $p = .164$, $d = 0.29$). All participants were compensated with € 100 or course credit points (in case of psychology students) for their participation. The experimental procedure was approved by the ethics committee at the University of Graz, Austria.

2.2. Psychometric test session

Participants' arithmetic competencies were assessed by a paper-pencil test (Vogel et al., 2017) that is based on the French Kit Test (French et al., 1963). This test includes 128 simple multiplications (i.e., consisting of two single-digit operands), 64 simple additions (i.e., consisting of two single-digit operands), 128 simple subtractions (i.e., consisting of an operand <20 and a single-digit operand), 60 complex multiplications (i.e., consisting of a double-digit and a single-digit operand), 60 complex additions (i.e., consisting of three double-digit operands) and 60 complex subtractions (i.e., consisting of two double-digit operands). Participants were instructed to solve as many problems as possible within a given time range (i.e., 90 s for each simple operation type; 120 s for each complex operation type). Participant selection was then based on the total number of correctly solved problems. For the current study, only participants whose performance ranged in the lowest and highest third of the participant pool were selected.

Apart from the arithmetic fluency task, participants also worked on an intelligence test (Berlin Intelligence Structure Test; Jäger et al., 1997), a test measuring knowledge in higher-order mathematics (Mathematics test for personnel selection; Jasper and Wagener, 2011), the German version of the NEO Five-Factor Inventory (Borkenau and Ostendorf, 1993), the German adaptation of the Abbreviated Math Anxiety Scale (AMAS-G; Schillinger et al., 2018), the Single-Item-Math Anxiety Scale (SIMA, Núñez-Peña et al., 2014), a test measuring the attitude towards mathematics (Núñez-Peña et al., 2013, 2014), the German Test Anxiety Inventory ("Prüfungsangstfragebogen", PAF; Hodapp et al., 2011) and the State-Trait Anxiety Inventory Trait scale (STAIT-T; Laux et al., 1981; Spielberger et al., 1983). Finally, participants were asked for their mathematics grade in their final high school exam.

To check for group differences, we performed *t*-tests for independent samples on all mathematical measures (i.e., arithmetic, higher-order mathematics, mathematics grade and numerical intelligence), on both math anxiety measures (i.e., AMAS-G and SIMA) as well as on verbal and figural intelligence. As evident in Table 1, the strongest difference between groups was observed for arithmetic (with an effect size of $d = 5.56$), as the groups were defined in this way. Therefore, the two groups can be regarded as extreme groups with respect to arithmetic. The differences in the higher-order mathematics and numerical intelligence were also very large (with $ds > 1$), while the difference in verbal intelligence was lower ($d = 0.84$).

2.3. Materials and procedure

All participants underwent a five-day multiplication facts training followed by an fMRI test session (see Fig. 1). The training was provided online so that participants were able to do the training at home. Each training session took about 20 min resulting in 100 min for the whole multiplication facts training. In the fMRI scanner, participants were asked to perform a multiplication verification task lasting about 40 min. Two comparable sets of stimuli were used for the training and the multiplication verification task, each consisting of 12 single-digit multiplication problems (see Appendix Table A.1) divided into 6 low and 6 high interfering problems. Stimuli were drawn from the 36 possible combinations of operands from 2 to 9 (without the commutative pairs). Further, the proactive interference parameter (IP; De Visscher et al., 2014) was used to define the interference level of the problems. Multiplications with an IP smaller than 8 were classified as low-interfering problems, whereas multiplications with an IP greater than or equal to 8 were classified as high-interfering problems.

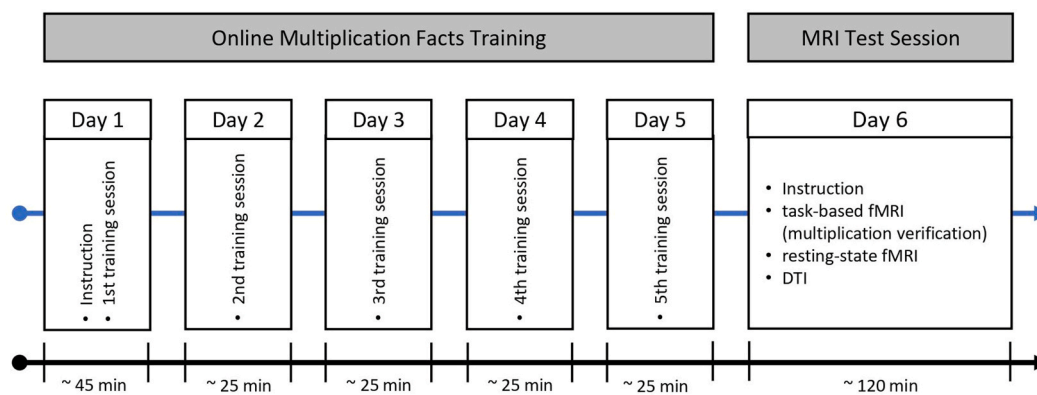
Table 1

Descriptive statistics for mathematical variables, verbal, and figural intelligence (raw values).

	Low Arithmetic Competence Group		High Arithmetic Competence group		<i>t</i>	<i>p</i>	<i>d</i>
	Mean	SD	Mean	SD			
Arithmetic	133.35	23.34	271.61	26.24	−18.88	.000	5.56
Higher-order mathematics	19.30	4.58	24.43	4.53	−3.82	.000	1.13
Mathematics grade ¹	2.87	0.81	2.13	0.92	2.89	.006	0.85
Numerical intelligence	33.52	12.25	54.04	14.18	−5.25	.000	1.55
Math anxiety (AMAS-G) ²	2.40	0.72	1.94	0.56	2.43	.019	0.71
Math anxiety (SIMA) ³	3.91	2.11	2.43	1.65	2.65	.011	0.78
Verbal intelligence	85.04	15.76	97.43	13.75	−2.84	.007	0.84
Figural intelligence	80.22	11.69	86.65	11.01	−1.92	.061	0.57

Note: ¹Characteristics of the Austrian grading system: 1 = Very good (highest grade), 2 = Good, 3 = Satisfactory, 4 = Adequate, 5 = Unsatisfactory (lowest grade);

²Score range: 1 (not anxious) to 5 (very anxious); ³Score range: 1 (not anxious) to 10 (very anxious); Abbreviations: AMAS-G = German adaptation of the Abbreviated Math Anxiety Scale, SIMA = Single-Item-Math Anxiety Scale.

**Fig. 1.** Time-course of an experimental session.

Additionally, problems were controlled for problem size meaning that small (products < 26) and large problems (products > 25) were equally distributed over both levels of interference (Campbell and Xue, 2001). Selected stimuli were then divided into two sets (i.e., Set 1 and Set 2) that were matched in terms of interference and problem size. Two independent *t*-tests showed that the interference level ($t(22) = -1.328$, $p = .198$, $r = 0.27$; Set 1: $M = 7.42$, $SD = 2.61$; Set 2: $M = 10.25$, $SD = 6.92$) and the problem size ($t(22) = -1.124$, $p = .273$, $r = 0.23$; Set 1: $M = 26.67$, $SD = 11.80$; Set 2: $M = 34.08$, $SD = 19.57$) did not differ significantly between both sets. At the beginning of the training, participants were randomly assigned to one of the two sets of stimuli. For each participant, the randomly assigned set of stimuli was then used for the online multiplication facts training and during the scanning session (trained set of stimuli), whereas the second set was only used in the scanner to compare trained and untrained stimuli. The assignment of sets was counterbalanced between participants so that half of them received Set 1 during the training while the other half received the Set 2.

2.3.1. Online multiplication facts training

The online multiplication facts training consisted of five training sessions distributed over five consecutive days. In the first training session, taking place at the laboratory of the section of Educational Neuroscience (University of Graz), participants were given detailed instructions concerning the online multiplication facts training. Specifically, they were instructed to increase speed and accuracy over training. To monitor their training progress, participants received a training protocol, where they had to record their general performance (solution time and accuracy) for each training session.

The training was programmed with jsPsych (de Leeuw, 2015). JsPsych is an open-source JavaScript Library that allows the implementation of behavioral experiments in a web browser. Within each training session, the set of 12 problems was presented 16 times, resulting

in 80 repetitions of each multiplication over the five days. Each training session was divided into 8 runs, in which each multiplication was presented twice. Every trial started with 500 ms (milliseconds) fixation followed by a multiplication problem (see Fig. 2). Participants were instructed to press the ENTER key to signal that they know the solution to the presented problem. Problem presentation was terminated by the press of the ENTER key, but at the latest after 5000 ms. Subsequently, within 5000 ms participants had to enter their solution in an input field and to confirm it by pressing the ENTER key. Afterwards, but at the latest after 5000 ms, participants received feedback about their performance. If participants' solution was correct, the German word 'Richtig' (correct) was displayed for 2000 ms. If participants' solution was incorrect, the German word 'Falsch' (wrong) was shown. In both cases the feedback was displayed together with the problem and its correct solution to support fact learning. At the end of each training session, participants received feedback about their general performance (mean solution time and accuracy), which they had to document in the training protocol, in order to motivate them.

2.3.1.1. Multiplication verification task. On the day following the training, an fMRI test session took place. In the scanner, participants worked on both sets (i.e., trained versus untrained set) of stimuli combined in a multiplication verification task. The merge of both sets allowed us to investigate training effects by comparing trained and untrained problems. Stimuli were presented with PsychoPy (version 1.83.4; Peirce, 2007, 2008) on a 32" Full HD LCD-Monitor that was situated behind the MRI scanner. Participants watched the stimuli presentation via a mirror device mounted on the head coil. The multiplication verification task took about 40 min and it was divided into 8 runs. Trained and untrained stimuli as well as their commutative pairs (i.e., 3×4 and 4×3) were presented four times, resulting in 196 trials overall. Every trial started with 500 ms fixation followed by a multiplication

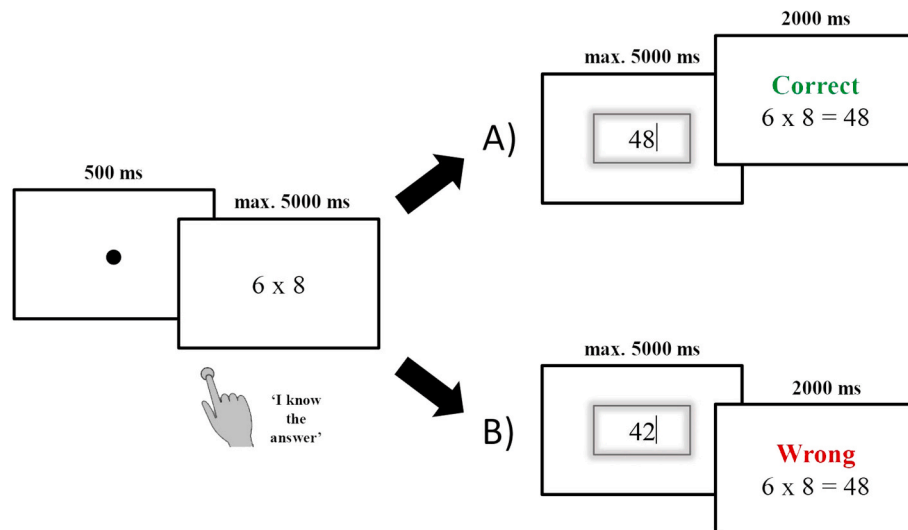


Fig. 2. Time-course of multiplication problems answered A) correctly and B) incorrectly in the training task.

problem (see Fig. 3). The multiplication remained visible until participants' button press. As in the online multiplication facts training, participants were instructed to press the button to signal that they knew the solution to the presented problem. The multiplication problem was then followed by a jittered inter-stimulus-interval (blank screen) with a mean duration of 2250 ms (500–4000 ms) and by a solution option presented for 1500 ms. In each run, half of the multiplications were followed by a correct solution, whereas the other half was followed by an incorrect solution (i.e., solution from another operand-related multiplication problem). Participants had to indicate whether the presented solution was correct or not. A jittered inter-stimulus-interval (blank screen) with a mean duration of 5000 ms (3000–7000 ms) was interspersed between trials. Problems were presented following a pseudo-random order so that no more than three successive problems were of the same type (i.e., low-high interfering, trained-untrained) and two successive problems never shared the same operands.

2.4. MRI acquisition

Neuroimaging data were collected with a 3-T Skyra (Siemens) and a 32-channel head coil at the MRI Lab of Graz. For collecting neurofunctional data we used an echo planar imaging (EPI) sequence (TE = 36.40 ms, flip angle = 60°, voxel size = 2.5 × 2.5 × 2.5 mm, FOV = 215, TR = 2000 ms, 52 slices, slice thickness = 2.5 mm). Additionally, T1 weighted anatomical scans were collected (TI = 950 ms, TE = 2.89 ms, TR = 1950

ms, flip angle = 12°, voxel size = 1.0 × 1.0 × 1.0 mm, FOV = 256 mm, 176 slices, slice thickness = 1.0 mm). Furthermore, we collected resting-state functional scans and diffusion-tensor weighted images, which were not analyzed here. The total duration of the MRI test session including instructions was 2 h.

2.5. Behavioral data analysis

Regarding the multiplication training data, we tested whether and to what extent competence-related differences in the interference effect were modulated by multiplication facts training. Therefore, mean response latencies of the behavioral data collected during the multiplication facts training were entered into a 2 (Group: low versus high) × 2 (Training session: first versus last training day) × 2 (Interference level: low versus high interfering) mixed measures Analysis of Variance (ANOVA).

Regarding the behavioral data collected in the scanner, through a multiplication verification task, we used a three-factorial design including Training status (trained versus untrained stimuli), Interference level (high versus low), and Group (high versus low). For both analyses, the response latencies between problem onset and first key press (i.e., the point at which participants indicated they knew the answer to the problem) was used.

Simple effect analyses adjusted for multiple comparisons (Bonferroni) were calculated to further elucidate interaction effects.

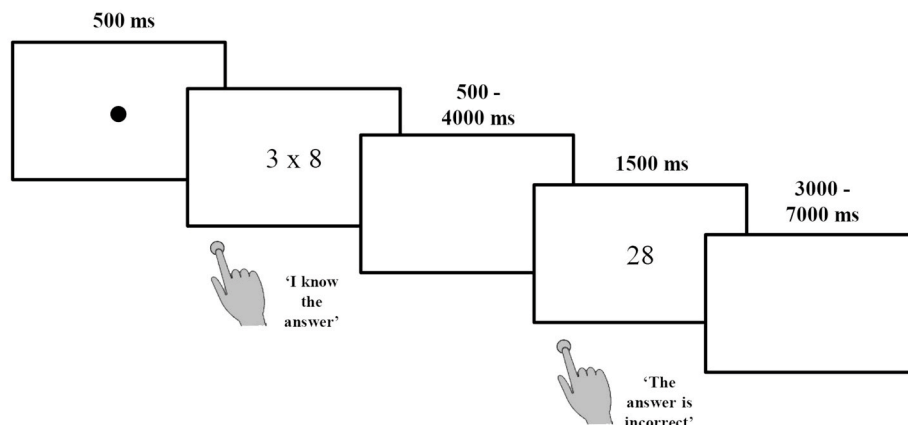


Fig. 3. Time-course of the multiplication verification task used in the fMRI scanner.

Due to an overall low error rate ($Max = 16$ out of 80) we refrained from analyzing accuracy data. Nevertheless, descriptive statistics on accuracy can be found in Table A.2 (multiplication facts training) and Table A.3 (multiplication verification task) in the appendix.

2.6. Imaging preprocessing

Preprocessing of the imaging data was carried out using the Data Processing Assistant for Resting-State fMRI (DPARSF, Yan and Zang, 2010, <http://rfmri.org/DPARSF>). This toolbox is based on the Statistical Parametric Mapping (SPM, Wellcome Department of Imaging Neuroscience, London, U.K.) software and the toolbox for Data Processing & Analysis of Brain Imaging (DPABI, C. G. Yan et al., 2016, <http://rfmri.org/DPABI>). First, each dataset was slice time corrected (referenced to the slice acquired at the middle time point) and spatially realigned. The resulting EPI volumes were then registered to the anatomical images and spatially transformed into standard space of the Montreal Neurological Institute (MNI) using the toolbox for “Diffeomorphic Anatomical Registration using Exponentiated Lie algebra” (DARTEL; Ashburner, 2007). Finally, the EPI images were smoothed with an 8.0 mm full-width-at-half-maximum (FWHM) gaussian kernel.

2.7. Functional data analysis

Statistical analyses were performed using SPM12. First, a first-level model of the fMRI data was produced in accordance with the general linear model. Correctly solved problems were grouped into the four experimental conditions according to Interference level (i.e., low vs high interfering) and Training status (trained vs untrained). Additionally, six rigid-body movement parameters and the errors for each experimental condition were entered as additional regressors of no interest. These events were then convolved with SPM’s canonical hemodynamic response function (HRF) to calculate HRF amplitude estimates. Furthermore, a 128 s high-pass filter was applied to remove low frequency modulations.

Second, we examined BOLD differences between groups of low and high arithmetic competencies as a function of interference and training. To this end, a mixed ANOVA with Group (low versus high arithmetic competencies) as between-subjects factor and Interference level (low versus high) and Training status (trained versus untrained problems) as within-subject factors was calculated. Statistical results of this second-level analysis are reported with family wise error (FWE) corrected values at the peak level ($p < .05$). The anatomical labels were assigned by referencing to the automated anatomical atlas (AAL; Tzourio-Mazoyer et al., 2002).

3. Results

3.1. Behavioral data

3.1.1. Multiplication facts training

Analysis of mean response latencies (i.e., the point at which participants indicated they knew the answer to the problem) revealed a significant main effect of Group ($F(1,44) = 24.35, p < .001, \eta_p^2 = 0.356$), indicating that participants of the low competent group had significantly longer response latencies ($M = 906$ ms) compared to participants of the high competent group ($M = 615$ ms). Additionally, the main effect of Training session was significant ($F(1,44) = 128.36, p < .001, \eta_p^2 = 0.745$), indicating that response latencies on the first day ($M = 948$ ms) were significantly longer compared to those on the last day ($M = 572$ ms). The main effect of Interference level ($F(1,44) = 51.23, p < .001, \eta_p^2 = 0.538$) was also significant, indicating that response latencies in low interfering multiplications ($M = 685$ ms) were significantly shorter compared to high interfering problems ($M = 835$ ms).

Furthermore, the analysis revealed a significant interaction effect between Group and Training session ($F(1,44) = 20.20, p < .001, \eta_p^2 =$

0.315), indicating a greater training-related decrease of response latencies in the low competent ($M_{\text{Difference}} = 526$ ms; $F(1,44) = 125.20, p < .001, \eta_p^2 = 0.740$) as compared with the high competent group ($M_{\text{Difference}} = 227$ ms; $F(1,44) = 23.36, p < .001, \eta_p^2 = 0.347$). In addition, the low competent group showed a bigger interference effect (i.e., absolute difference in response latencies between low and high interfering problems) as compared to the high competent group (Group x Interference level: $F(1,44) = 18.37, p < .001, \eta_p^2 = 0.295$), and the interference effect on the first day of the training was larger as compared to the interference effect on the last day (Training session x Interference level: $F(1,44) = 27.81, p < .001, \eta_p^2 = 0.387$).

Most importantly, a significant three-way interaction between Group, Training session, and Interference level emerged ($F(1,44) = 11.28, p < .01, \eta_p^2 = 0.204$; see Fig. 4). This interaction revealed that the low competent group showed a significant and strong interference effect (i.e., longer response latencies for high-interfering problems compared to low-interfering ones) not only on the first ($F(1,44) = 56.15, p < .001, \eta_p^2 = 0.561$; low interfering problems: $M = 975$ ms; high interfering problems: $M = 1362$ ms) but also on the last day ($F(1,44) = 34.46, p < .001, \eta_p^2 = 0.439$; low interfering problems: $M = 596$ ms; high interfering problems: $M = 689$ ms) of the training, whereas the interference effect in the high competent group was much smaller and not significant (day 1: $F(1,44) = 3.23, p = .079, \eta_p^2 = 0.068$; low interfering problems: $M = 682$ ms; high interfering problems: $M = 775$ ms; day 5: $F(1,44) = 3.04, p = .088, \eta_p^2 = 0.065$; low interfering problems: $M = 487$ ms; high interfering problems: $M = 515$ ms). Overall, these results indicate that the interference effect in the low competent group was large compared to the high competent group, and robust since the training reduced it but did not suppress it.

3.1.2. Multiplication verification task during fMRI

The second analysis focused on the behavioral data in the fMRI test session and aimed to investigate competence-related differences in the interference effect in trained and untrained multiplications. As expected, the main effect of Group ($F(1,44) = 11.64, p < .01, \eta_p^2 = 0.209$) was significant, indicating that response latencies of participants of the low competent group were larger ($M = 847$ ms) compared to those of participants of the high competent group ($M = 594$ ms). Analyses also revealed a significant main effect of Training status ($F(1,44) = 12.11, p < .01, \eta_p^2 = 0.216$), showing that response latencies for trained multiplication problems were significantly shorter ($M = 699$ ms) compared to untrained multiplication problems ($M = 742$ ms), and a significant main effect of Interference level ($F(1,44) = 12.05, p < .01, \eta_p^2 = 0.215$), indicating that response latencies for low interfering problems ($M = 670$ ms) were significantly shorter compared to high interfering problems ($M = 771$ ms). These results witness that the task worked as predicted. More importantly, a significant interaction effect between Group and Training status ($F(1,44) = 4.43, p < .05, \eta_p^2 = 0.091$; see Fig. 5) and between Group and Interference level was found ($F(1,44) = 6.02, p < .05, \eta_p^2 = 0.120$; see Fig. 5). Simple effect analyses showed that in the low competent group, response latencies for trained multiplications ($F(1,44) = 15.59, p < .001, \eta_p^2 = 0.262$; $M = 813$ ms) were significantly shorter compared to untrained ones ($M = 881$ ms), and participants of the low competent group needed longer time to solve high-interfering problems ($F(1,44) = 17.55, p < .001, \eta_p^2 = 0.285$; $M = 933$ ms) compared to low-interfering ones ($M = 761$ ms). In contrast to these results, the high competent group did not show significant differences between trained and untrained problems ($F(1,44) = 0.95, p = .336, \eta_p^2 = 0.021$; trained problems: $M = 586$ ms; untrained problems: $M = 602$) and between low and high interfering problems ($F(1,44) = 0.52, p = .475, \eta_p^2 = 0.012$; low interfering problems: $M = 579$ ms; high interfering problems: $M = 609$). In general, these results indicate that response latencies for multiplications were differently affected by training when comparing low and high competent individuals. Whereas the low competent group showed a training effect, retrieval times for trained and untrained multiplications did not differ in the high competent group. Further, the low competent group showed an interference effect unaffected by training, whereas the

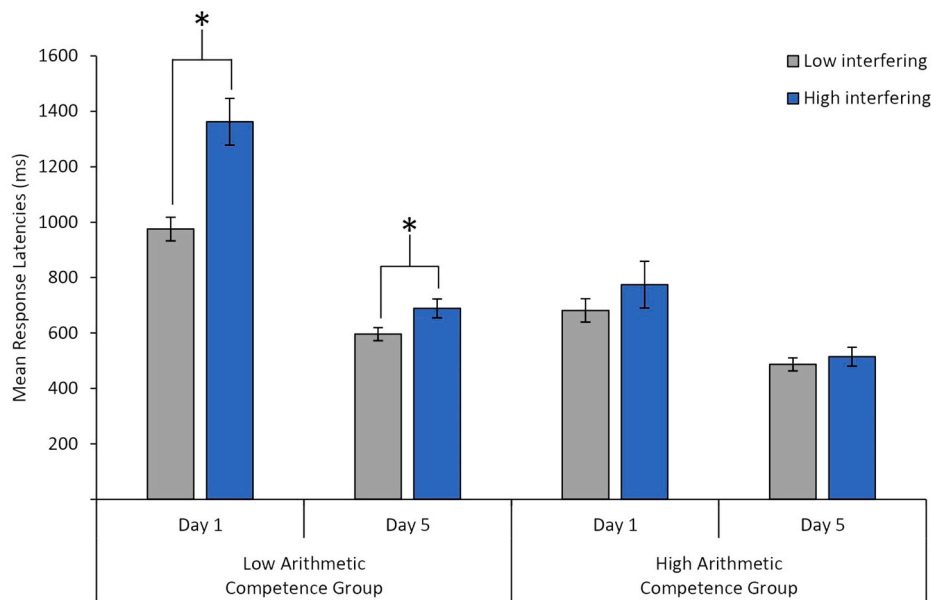


Fig. 4. Mean response latencies for each competence group separately for low and high-interfering multiplications and for the first and last training day; * $p < .05$ (Bonferroni corrected).

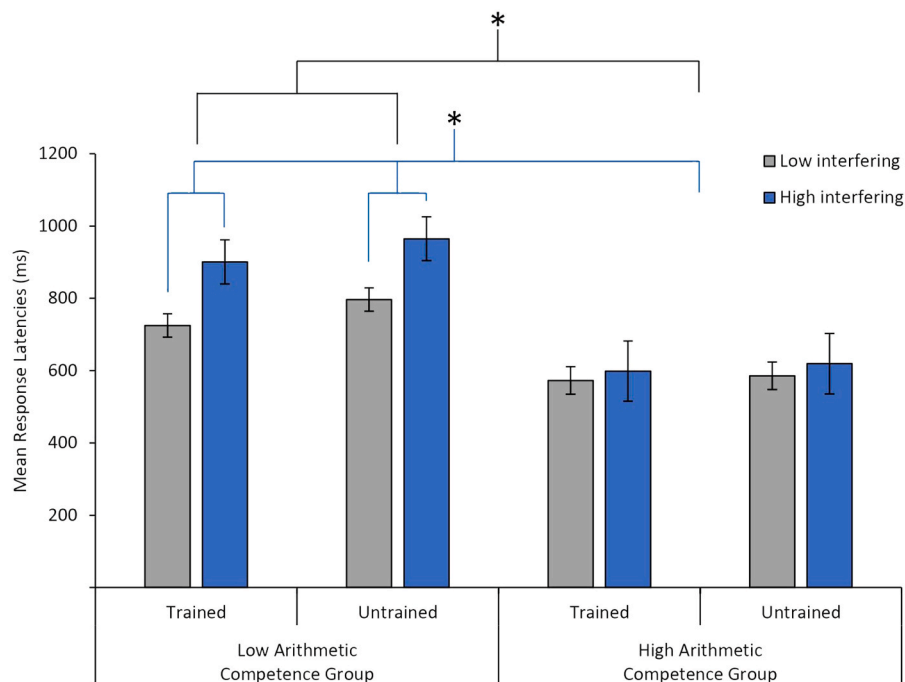


Fig. 5. Mean response latencies for each competence group separately for trained and untrained as well as low and high-interfering multiplication problems. Black line: Group $\times$ Training status, blue line: Group $\times$ Interference level, * $p < .05$ (Bonferroni corrected). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

high competent group did again not show an interference effect at all. Interestingly, there was no significant interaction effect between Training status and Interference level ($F(1,44) = 0.00$, $p = .995$, $\eta_p^2 = 0.000$) and no three-way interaction effect between Group, Training status and Interference level ($F(1,44) = 0.16$, $p = .689$, $\eta_p^2 = 0.004$).

3.2. Imaging data

3.2.1. Main effects of training, interference, and competence group

We first identified brain regions that were associated with a

significant main effect of Training status. The right and left supra-marginal gyrus, both extending to the angular gyri as well as the left superior frontal gyrus (medial part), the left amygdala and the left insula lobe showed higher neural activity to trained compared to untrained multiplications (see Table 2A). For the reverse contrast (i.e., untrained $>$ trained), significant brain activation was found in a widespread bilateral fronto-parietal network including the supplementary motor areas, the insulae (including the IFG) and the precunei. Moreover, greater brain activity was found in the left precentral gyrus, the left middle occipital gyrus, and the left middle frontal gyrus.

We then calculated the brain regions that showed a significant main effect of Interference level. The left and right supramarginal gyrus showed higher neural activity in the low interfering compared to the high interfering condition (see Table 2B). For the reverse contrast (i.e., high > low interfering multiplications), analysis revealed significant greater brain activity again in a widespread fronto-parietal network. More specifically, bilateral brain activations were observed in the

supplementary motor areas, the insulae (including the IFG) and the precune. Additionally, left hemispheric neural activity was found significant in the precentral gyrus, the middle frontal gyrus, and the middle occipital gyrus, whereas significant right hemispheric brain activity was observed in the cerebellum.

No significant activation differences were found for the main effect of Group.

Table 2

Brain regions associated with A) the main effect of Training status and B) the main effect of Interference level.

Contrast	Brain Region	Cluster (%)	Extent	t-value	x	y	z
A) Training status trained > untrained	R Supramarginal gyrus	80.18	338	6.04	58	-30	28
	R Angular gyrus	5.33					
	L Amygdala	60.00	30	6.04	-25	-5	-23
	L Hippocampus	33.33					
	L Superior frontal gyrus (medial part)	50.00	52	5.53	-8	58	3
	L Anterior cingulate cortex (pregenual)	40.38					
	L Superior frontal gyrus (medial orbital)	9.62					
	L Supramarginal gyrus	75.00	40	5.33	-63	-30	28
	L Insula	78.57	14	5.16	-35	3	15
	L Rolandic operculum	21.43					
	L Angular gyrus	100.00	11	4.82	-55	-63	30
	L Supplementary motor area	28.22	691	7.16	-3	18	48
	R Middle cingulate & paracingulate gyrus	22.58					
	L Superior frontal gyrus (medial part)	16.35					
	R Supplementary motor area	15.20					
	L Middle cingulate & paracingulate gyrus	8.83					
	L Precuneus	33.51	379	6.51	-13	-60	23
	R Precuneus	27.18					
	L Cuneus	24.27					
	L Insula	77.27	198	6.50	-33	23	3
	L Inferior frontal gyrus (pars triangularis)	12.63					
	R Insula	59.16	191	6.43	40	15	5
	R Inferior frontal gyrus (pars opercularis)	11.52					
	R Inferior frontal gyrus (pars triangularis)	5.76					
	L Precentral gyrus	40.62	325	6.22	-43	8	30
	L Inferior frontal gyrus (pars triangularis)	31.38					
	L Inferior frontal gyrus (pars opercularis)	20.92					
	L Middle occipital gyrus	68.84	138	5.72	-30	-73	38
	L Inferior parietal gyrus	26.09					
	L Middle frontal gyrus	81.82	55	5.63	-30	5	63
	L Superior frontal gyrus	14.55					
	R Cerebellum	100.00	16	5.21	30	-60	-28
B) Interference level low > high interfering	L Supramarginal gyrus	94.12	51	5.25	-58	-30	28
	L Superior temporal gyrus	5.88					
	R Supramarginal gyrus	98.33	60	5.22	58	-30	38
	L Supplementary motor area	28.22	691	7.16	-3	18	48
	R Middle cingulate & paracingulate gyrus	22.58					
	L Superior frontal gyrus (medial part)	16.35					
	R Supplementary motor area	15.20					
	L Middle cingulate & paracingulate gyrus	8.83					
	L Precuneus	33.51	379	6.51	-13	-60	23
	R Precuneus	27.18					
	L Cuneus	24.27					
	L Insula	77.27	198	6.50	-33	23	3
	L Inferior frontal gyrus (pars triangularis)	12.63					
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	R Inferior frontal gyrus (pars opercularis)	11.52					
	R Inferior frontal gyrus (pars triangularis)	5.76					
	L Precentral gyrus	40.62	325	6.22	-43	8	30
	L Inferior frontal gyrus (pars triangularis)	31.38					
	L Inferior frontal gyrus (pars opercularis)	20.92					
	L Middle occipital gyrus	68.84	138	5.72	-30	-73	38
	L Inferior parietal gyrus	26.09					
	L Middle frontal gyrus	81.82	55	5.63	-30	5	63
	L Superior frontal gyrus	14.55					
	R Cerebellum	100.00	16	5.21	30	-60	-28

Notes: Coordinates refer to the activation peak of the cluster and are reported in MNI (Montreal Neurological Institute) space as given by SPM12. The anatomical localization is presented based on the AAL (automated anatomical labeling) atlas (Tzourio-Mazoyer et al., 2002). The first label denotes the location of the peak activation, further labels indicate different brain regions within the same activation cluster (including submaxima) if the percentage of activated voxels within the cluster is > 5.00. Only activation clusters significant at $p < .05$ FWE corrected for multiple comparisons at peak level and $k > 10$ voxels are reported. Abbreviations: L = left hemisphere; R = right hemisphere.

3.2.2. Interaction effects

In the analyses investigating interaction effects no voxel survived whole-brain FWE-corrected thresholds at peak level. Therefore, a less conservative threshold of $p < .001$ (uncorrected) was applied and activations that survived FWE correction ($p < .05$) at the cluster level were reported. Analyses revealed an interaction effect between Group and Training status in the right supramarginal gyrus (MNI(x,y,z): 60, -40, 35; $F(1,176) = 22.26$; $Z = 4.42$; $k = 167$) and an interaction effect between Group and Interference level in the left supramarginal gyrus (MNI(x,y,z): 60, -38, 35; $F(1,176) = 17.76$; $Z = 3.94$; $k = 204$). These interaction effects indicate that the neural training effect in the right supramarginal gyrus and the neural interference effect in the left supramarginal gyrus are modulated by individual differences in arithmetic competencies. Post-hoc analyses of percent signal changes (PSC) extracted from these cortical regions showed significant within-subject differences only for the low competent group (see Fig. 6A & B). More precisely, the neural activity in the right supramarginal gyrus was significantly increased in the trained condition compared to the untrained condition ($t(22) = 7.00$, $p < .001$, $r = 0.83$), whereas neural activity in the left supramarginal gyrus was significantly increased for low interfering compared to high interfering problems ($t(22) = 7.23$, $p < .001$, $r = 0.84$). For the high competent group there was no significant difference between trained and untrained multiplications ($t(22) = 0.64$, $p = .531$, $r = 0.14$) and no significant difference between low and high

interfering problems ($t(22) = -0.14$, $p = .893$, $r = 0.03$). Furthermore, significant differences between groups were revealed for untrained multiplications ($t(44) = -2.45$, $p < .05$, $r = 0.35$) and high interfering problems ($t(44) = -2.22$, $p < .05$, $r = 0.32$). There were no significant group differences for trained ($t(44) = -0.33$, $p = .740$, $r = 0.05$) and low interfering problems ($t(44) = -0.69$, $p = .491$, $r = 0.10$).

Even by using a less conservative threshold no three-way interaction effect was observed.

4. Discussion

Arithmetic facts are a major building block for mathematical cognition that allow us to solve mathematical equations swiftly and effortlessly (Domahs and Delazer, 2005). According to De Visscher and Noël (2013), individual differences in arithmetic fact knowledge are partly due to differences in sensitivity to interference when storing and manipulating memory representations of arithmetic facts. Individuals with lower (as compared to higher) arithmetic competencies have been found to show larger interference effects in multiplication problem solving in both performance (De Visscher and Noël, 2014b) and brain activation (De Visscher et al., 2018). The aim of the present study was to examine whether an intensive practice of high-interfering multiplication problems reduces competence-related differences in the behavioral and neural interference effects. To that aim, two groups of adults differing in

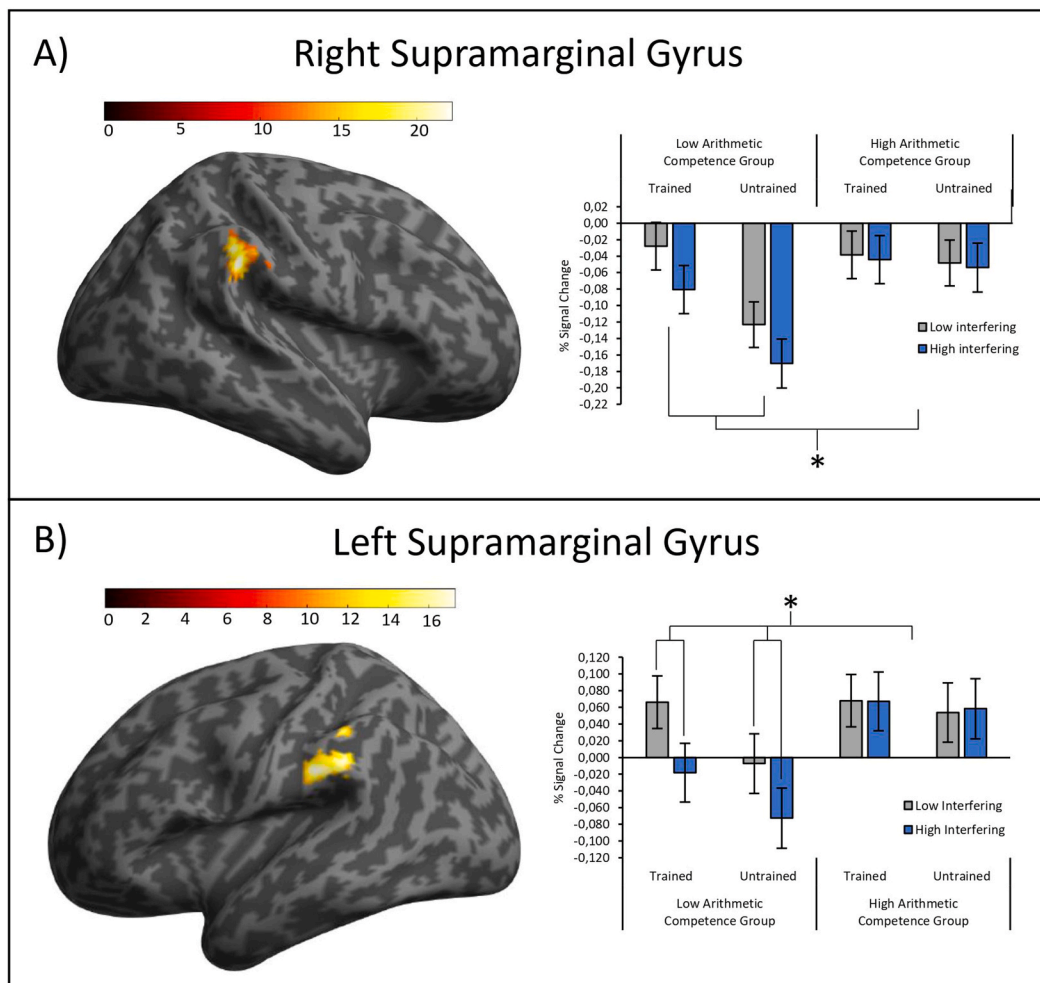


Fig. 6. A) Neural interaction between Group and training effect in the right supramarginal gyrus ($p < .05$ FWE cluster corrected). Percent signal change in the four experimental conditions were extracted from the activated cluster and are displayed as a function of the experimental conditions (* $p < .001$). B) Neural interaction between Group and interference effect in the left supramarginal gyrus ($p < .05$ FWE cluster corrected). Percent signal change in the four experimental conditions were extracted from the activated cluster and are displayed as a function of the experimental conditions (* $p < .001$).

their arithmetic competencies (low versus high) underwent a five-day training, in which they practiced sets of low and high interfering multiplication facts. In the fMRI session after the training, participants performed a multiplication verification task containing trained and untrained problems of both interference levels.

However, before we discuss the results of the present study, it is important to mention that besides arithmetic and mathematical competencies, both groups also differed in verbal intelligence, though to a much lower extent. The association between verbal ability and arithmetic competence is not unexpected (see De Smedt, 2018, for a discussion) and associations between phonological processing and arithmetic have been reported in children (e.g., De Smedt et al., 2010) and adults (e.g., De Smedt and Boets, 2010). To analyze whether the difference in verbal intelligence influenced our results, we additionally ran Analyses of Covariance (ANCOVA) with verbal intelligence as a covariate on the behavioral as well as on the neural data. Importantly, neither for the behavioral nor for the neural data verbal intelligence was found to be a significant covariate. This suggests that the current findings cannot be explained by individual differences in verbal intelligence between the low and high arithmetic competence groups.

Overall, training and interference effects were confirmed by the behavioral data collected during the training session and the fMRI session. Over the course of the training both individuals from low and high competent groups showed a decrease in response latencies and in the training as well as in the fMRI session low interfering multiplications were solved faster as compared to high interfering problems. However, both effects showed a modulation due to group differences. Low competent individuals were significantly faster in generating solutions to trained multiplications compared to untrained problems, whereas high competent individuals showed an equally fast solution time for both problem types. Likewise, the interference effect was only observed for low competent individuals both during training and in the fMRI session. This result is in line with previous findings showing that people with poor arithmetic competencies are particularly sensitive to interference (De Visscher and Noël, 2014b). The analysis of the behavioral training data also showed a significant three-way interaction between Group, Interference level and Training session, suggesting that the interference effect in the low competent group changed across the training. However, even though the low competent group became faster in solving high interfering multiplications, the interference effect did not disappear. Rather, it was strong at both time points and only showed a slight decrease in effect size (as indicated in the η_p^2 values). In line with this, the behavioral data collected during the fMRI session did not show any influence of training on the interference effect in individuals with low arithmetic competence. One might have expected that in the low competent group there is an interference effect in the untrained problems (similar to day 1) but a weaker one in the trained problems (similar to day 5). This novel finding therefore suggests that the interference effect reflects an aspect of cognitive processing that is not so easy to change by a multiple-day drill training of arithmetic facts.

At the neural level, we found a significant effect of training. Solving trained compared to untrained problems was accompanied by higher activation, *inter alia*, in the left and right inferior parietal lobe (i.e., SMG and AG). The reverse contrast showed increased activation in a bilateral network including frontal (e.g., supplementary motor areas, IFG) as well as parietal brain regions (e.g., precune). These activation differences are in line with our hypothesis and the findings of previous training studies showing that intensive practice of arithmetic problems leads to a decrease in deactivation in the SMG and AG (for trained problems), whereas untrained problems more strongly recruit a widespread frontoparietal network (e.g., Delazer et al., 2003; 2005; Grabner et al., 2009a, b; Ischebeck et al., 2006). Thus, it supports the general idea that intensive practice leads to an increasing automaticity in the retrieval of arithmetic problems (Zamarian et al., 2009). However, the neural training effect turned out to be depend on the individual's level of arithmetic competence. Analyses revealed that the right SMG showed an

interaction between training and competence group, reflecting a higher neural training effect in low performers as compared to high performers. Closer examination of percent signal changes revealed that training-related increases in activation were actually decreases of deactivation and that the interaction mainly emerged from less right SMG deactivation for untrained multiplication problems in the high compared to the low competent group. In other words, while low and high competent individuals showed an equally strong deactivation while solving trained problems, in the untrained problems the low competent group showed a stronger deactivation than the high competent group. This finding suggests that in the group with low arithmetic competencies training led to increased automaticity in the retrieval of trained multiplications reflected by a decrease in deactivation.

Changes in deactivation in both the left and right SMG (together with the AG) have been detected in many other arithmetic studies (Bloechle et al., 2016; Grabner et al., 2009a,b; Pesenti et al., 2001; Rickard et al., 2000; Rivera et al., 2005; van Harskamp et al., 2002) and they have been linked to processes supporting memory retrieval (Ischebeck et al., 2007). Similar to the current study, two studies (Ischebeck et al., 2007; Rickard et al., 2000) have observed deactivation in the right SMG while participants worked on a multiplication verification task. Whereas Rickard et al. (2000) found increased deactivation in the right SMG for a multiplication verification task relative to two low-level control tasks (i.e., numerical judgment and perceptual-motor control task), Ischebeck et al. (2007) observed decreased deactivation in the same brain region for repeated (trained) multiplications as compared to novel ones.¹

In contrast to previous findings (Grabner et al., 2007; Grabner et al., 2009a,b), we did not observe any relationship between individual differences in arithmetic competence and activation in the AG. However, the competence-related training effect observed in the right SMG shows a high similarity with the findings from the arithmetic fact training study by Grabner, Ischebeck and colleagues (2009). They reported a region-of-interest analysis of the left AG revealing that individuals with lower compared to higher mathematical competencies showed differences in deactivation only in the untrained (but not in the trained) problems, with the lower competence group exhibiting a stronger deactivation. In the trained problems (i.e., two-digits times one-digit problems, e.g., 12×6), in contrast, both groups showed a similar and small level of deactivation. The attenuation of competence-related differences in left AG deactivation due to training was interpreted to reflect the stronger reliance on fact retrieval in the less competent participants. Given the aforementioned evidence of a link between the SMG and (arithmetic) knowledge retrieval, Grabner et al.'s conclusion may also hold true for the interaction between individual differences in arithmetic competence and training observed in the present study. Specifically, the results suggest that the two competence groups differed in their reliance on fact retrieval before training (as is reflected in the untrained problems) but showed similar retrieval activity after the fact training. However, the discrepancy between the observation of the current study and Grabner et al.'s findings might be due to differences in fMRI data analysis and training materials. For example, Grabner et al. (2009a,b) performed region-of-interest analysis to investigate the learning of complex (multi-digit) multiplication problems, while in the current study FWE-corrected whole brain analyses were performed and "overlearned" multiplication tables (single-digit) as stimuli were used.

The fMRI data also revealed an effect of the problems' interference level that is in line with our hypothesis and previous studies by De Visscher et al. (2015, 2018). Firstly, similar to the present results, in both studies higher bilateral neural activity in the supplementary motor areas and the IFG as well as higher activation in the left middle frontal gyrus for high interfering problems as compared to low interfering ones

¹ It should be noted that beside other brain regions (e.g., the AG) the SMG is often found to be deactivated during task performance when compared to a less demanding condition (for a review see Gusnard and Raichle, 2001).

were observed. These brain regions are frequently reported in the literature on arithmetic problem solving (Arsalidou and Taylor, 2011) and are typically associated with domain-general processes (e.g., task difficulty; Fox et al., 2005). Secondly, De Visscher et al. (2018) reported greater BOLD response in the right SMG for low interfering multiplications as compared to high interfering ones, which we also observed. In contrast to our expectation and De Visscher et al. (2018), an interaction between interference and competence group was not observed in the left IFG but in the left SMG. Specifically, we found equally strong activation during low and high interfering problems in the high performers. Furthermore, low performers showed equally strong activation during low interfering problems as high performers during low and high interfering problems. Interestingly, significant differences were only observed for high interfering problems displaying a large deactivation in low competent individuals. Thus, alike the competence by training interaction, the type of problem (in this case low versus high interfering) affected activation only in the low competent individuals.

Activation in the left SMG has been found to involved in processing phonological inputs and outputs, such as articulatory sequencing, auditory short-term memory or the integration of sublexical and lexical cues (Oberhuber et al., 2016). Moreover and most importantly, left SMG activation has also been linked to bottom-up attention by information entering working memory from long-term memory (Cabeza et al., 2012) and was found to be associated with retrieval-based arithmetic (Delazer et al., 2005; Grabner et al., 2013). Grabner et al. (2013), for instance, suggested that the left SMG (together with the AG) mediates the automatic mapping of arithmetic problems onto answers stored in memory. Thus, a higher activity during arithmetic problem solving within these brain regions may reflect processes associated with retrieval of arithmetic facts from semantic long-term memory. In addition, there is evidence that activity within the left SMG is modulated by individual differences (Evans et al., 2014; Price et al., 2013; Rivera et al., 2005). For instance, Price et al. (2013) identified competence-related differences in left SMG activity during single-digit addition and subtraction. Individuals with higher scores in a national mathematics test showed greater activation in the left SMG. In addition, they found a negative correlation between mathematical competence and arithmetic activation in the right IPS. Based on these findings, Price et al. (2013) concluded that individuals with higher mathematical competencies recruit neural mechanisms associated with memory retrieval to solve additions and subtractions, whereas low performers rely on neural structures associated with more effortful procedural strategies. The present results are in concert with previous studies by showing that individuals with low and high arithmetic competencies differentially engage neural mechanisms associated with different strategies to solve arithmetic problems. Moreover, the competence-related modulation of the interference effect in the left SMG demonstrates that high interfering problems were solved differently in low competent individuals, which may reflect that these problems are less well represented in their semantic memory. The lack of an activation difference between both problem types in the high AC group, in contrast, suggests that these individuals had successfully stored low and high interfering multiplications and could rely on fact retrieval in both types of problems.

The little effect of the 5-day arithmetic fact training on the interference effect in individuals with low arithmetic competencies raises the question of which training approaches may be more fruitful in this endeavor. Training studies in the field of neuropsychological rehabilitation (Domahs et al., 2004, 2008; Girelli et al., 2002; Zaubmuller et al., 2009) are a great source for gathering ideas for alternative interventions. For instance, in a single case study Domahs et al. (2008) provided a 81-year-old patient with auditory cues in the rehabilitation of an acquired (after a stroke) impairment of multiplication fact retrieval. Auditory cues preceded multiplication problems and were used in

addition to conventional drill approach. Besides a general improvement due to the numerous repetitions of problems, the authors also found specific training effects linked to the presentation of auditory cues. This facilitation effect was attributed to the additional involvement of implicit memory systems and the modulation of attentional processes. Another possible way to resolve interference in arithmetic facts could be the training of cognitive control functions (i.e., resistance to proactive interference) in general. This is of particular interest, since previous findings (De Visscher and Noël, 2014a; Passolunghi & Siegel, 2001, 2004) suggest that the interference effect is a more domain-general phenomenon (linked to cognitive control functions) rather than a domain-specific one, which only affects the memorization of arithmetic facts. For instance, children with low arithmetic facts fluency also show a higher interference effect in a non-numerical associative memory task than controls (De Visscher and Noël, 2014a). Similarly, Passolunghi and Siegel (2001, 2004) reported a deficit in the ability to inhibit irrelevant information in memory during a listening span task in a group of children with mathematical difficulties when compared with typically developed children. Although eliminating proactive interference in arithmetic facts through an overall improvement of cognitive control functions seems very promising, inconsistent results on transfer effects have been reported (Enge et al., 2014; Redick et al., 2020; Thorell et al., 2009; Zhao and Jia, 2019). Thus, a more fruitful avenue might be the combination of training methods that target domain-general control functions as well as domain-specific processes. For example, adding an element of control into an arithmetic training.

In conclusion, the current study provided first evidence for a persistent interference effect in a group of young adults with low arithmetic competencies. The interference effect was present at both the behavioral and neurofunctional level and could not be resolved through a 5-days arithmetic facts training. This indicates that learning by rote does not fully help them to overcome the interference effect and to build up efficient memory representations. In the adults with high arithmetic competencies, in contrast, the interference level of the multiplication problems did neither affect performance nor brain activation, suggesting that they had built strong memory representations for these problems. Stronger activation for low compared to high interfering problems and competence-related differences in the interference effect were observed in the left SMG, adding to the evidence that the left SMG (together with the AG) supports arithmetic fact retrieval. Future training studies should aim to examine the effectiveness of conceptual methods to reduce interference instead of drill-based approaches.

Credit author statement

Alexander E. Heidekum: Conceptualization; Data curation; Formal analysis; Investigation; Writing – original draft; Visualization. Alice De Visscher: Conceptualization; Funding acquisition; Writing – review & editing. Stephan E. Vogel: Conceptualization; Funding acquisition; Writing – original draft; Writing – review & editing. Bert De Smedt: Conceptualization; Funding acquisition; Project administration; Writing – review & editing. Roland H. Grabner: Conceptualization; Funding acquisition; Project administration; Supervision; Writing – review & editing.

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7. Appendix

Table A.1

Experimental stimuli of the online multiplication facts training and the multiplication verification task

	Low interfering				High interfering			
	Problem	Size (product)	Size (category)	Interference Level	Problem	Size (product)	Size (category)	Interference Level
Set 1	$2 \times 6 =$	12	small	3	$3 \times 4 =$	12	small	10
	$4 \times 4 =$	16	small	5	$4 \times 5 =$	20	small	8
	$2 \times 9 =$	18	small	7	$4 \times 6 =$	24	small	12
	$5 \times 6 =$	30	large	6	$3 \times 9 =$	27	large	9
	$6 \times 6 =$	36	large	4	$4 \times 9 =$	36	large	9
	$7 \times 7 =$	49	large	7	$5 \times 8 =$	40	large	9
Set 2	$2 \times 7 =$	14	small	4	$3 \times 6 =$	18	small	8
	$2 \times 8 =$	16	small	7	$3 \times 7 =$	21	small	13
	$5 \times 5 =$	25	small	3	$3 \times 8 =$	24	small	13
	$5 \times 7 =$	35	large	7	$4 \times 8 =$	32	large	25
	$5 \times 9 =$	45	large	6	$7 \times 8 =$	56	large	9
	$9 \times 9 =$	81	large	6	$6 \times 7 =$	42	large	22

Table A.2

Mean accuracy (in percent) for each group separately for low and high-interfering multiplications and for the first and last training day.

	Low Arithmetic Competence Group		High Arithmetic Competence Group	
	low IF	high IF	low IF	high IF
1st day	98.87 (1.25)	95.85 (4.39)	98.96 (1.19)	97.91 (2.43)
5th day	99.13 (1.36)	98.26 (2.20)	99.13 (1.29)	98.70 (1.61)

Notes: Standard deviations in brackets. Abbreviation: IF = interfering.

Table A.3

Mean accuracy (in percent) for each group separately for low and high-interfering and for trained and untrained multiplications.

	Low Arithmetic Competence Group		High Arithmetic Competence Group	
	low IF	high IF	low IF	high IF
trained	97.83 (2.39)	97.46 (3.26)	97.74 (1.88)	98.55 (1.71)
untrained	96.29 (3.07)	94.75 (6.64)	98.01 (2.47)	98.73 (1.50)

Notes: Standard deviations in brackets. Abbreviation: IF = interfering.

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