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Flexible transfer of knowledge in mental arithmetic — An fMRI study

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ABSTRACT

Recent imaging studies could show that fact acquisition in arithmetic is associated with decreasing activation in several frontal and parietal areas, and relatively increasing activation within the angular gyrus, indicating a switch from direct calculation to retrieval of a learned fact from memory. So far, however, little is known about the transfer of learned facts between arithmetic operations. The aim of the present fMRI study was to investigate whether and how newly acquired arithmetic knowledge might transfer from trained multiplication problems to related division problems. On the day before scanning, ten complex multiplication problems were trained. Within the scanner, trained multiplication problems were compared with untrained multiplication problems, and division problems related to multiplication (transfer condition) were compared with unrelated division problems (no-transfer condition). Replicating earlier results, untrained multiplication problems activated several frontal and parietal brain areas more strongly than trained multiplication problems, while trained multiplication problems showed relatively stronger activation in the left angular gyrus than untrained multiplication problems. Concerning division, an ROI analysis indicated that activation in the left angular gyrus was relatively stronger for the transfer condition than for the no-transfer condition. We also observed distinct inter-individual differences with regard to transfer that modulated activation within the left angular gyrus. Activation within the left angular gyrus was generally higher for participants who showed a transfer effect for division problems. In conclusion, the present study yielded some evidence that successful transfer of knowledge between arithmetic operations is accompanied by modifications of brain activation patterns. The left angular gyrus seems not only to be involved in the retrieval of stored arithmetic facts, but also in the transfer between arithmetic operations.

Introduction

Although recent brain imaging research has contributed significantly to our understanding of the cerebral networks involved in number processing and the acquisition of arithmetic facts, a key feature of mathematical expertise, namely the transfer between arithmetic operations, has remained unexplored so far. In the present study we investigated whether newly acquired arithmetic fact knowledge from trained multiplication problems (e.g., $19\times4=76$) transfers to related division problems ($76:4=?$), and how brain activation patterns differ between division problems where transfer is possible and new, unrelated division problems.

Evidence from neuropsychological as well as brain imaging studies indicate that a range of fronto-parietal areas together with the basal ganglia play a role in arithmetic processing (for a review, e.g., Dehaene et al., 2003). When simple and complex arithmetic problems are solved, strong activation is observed within fronto-parietal areas (e.g., Chochon et al., 1999; Gruber et al., 2001). Within the parietal lobe, the intraparietal sulci are assumed to host a mental representation of quantity (see, for reviews, Ansari, 2008; Dehaene et al., 2004; see also Piazza et al., 2004). The stronger activation observed within frontal areas in calculation tasks has been interpreted as reflecting working memory demands (e.g., Kazui et al., 2000), error monitoring as well as strategic organization (e.g., Rickard et al., 2000). Perisylvian language areas and the left angular gyrus are assumed to be involved in the retrieval from long-term memory of overlearned arithmetic facts, such as the multiplication tables (Dehaene and Cohen, 1997). The basal ganglia are also critical to mental calculation as the disruption of cortico-subcortical loops by lesions to this brain structure can impair conceptual understanding of arithmetic as well as fact retrieval (e.g., Delazer et al., 2004).

Recent functional magnetic resonance imaging (fMRI) studies investigated learning effects in arithmetic. In these studies, typically, activation for previously trained problems is compared with activation for untrained problems (Delazer et al., 2003, 2005; Ischebeck et al., 2006). During the training phase, participants were asked to repeatedly produce the result to complex multiplication problems such as, e.g., 13×7. They trained on a computer for a total duration of approximately 1 h per day on consecutive 5 days before entering the

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scanner (Delazer et al., 2003, 2005; Ischebeck et al., 2006). In the fMRI study, untrained problems showed stronger activation than previously trained problems in fronto-parietal areas such as the intraparietal sulci and the left inferior frontal gyrus. Trained multiplication problems, on the other hand, showed relatively stronger activation in the left angular gyrus than untrained problems. This change in activation patterns was interpreted to represent a shift from calculation to result retrieval from long-term memory. Furthermore, these studies showed that the observed relative increase in activation in the left angular gyrus depended on the method of training (Delazer et al., 2005) as well as on the arithmetic operation being trained (Ischebeck et al., 2006). In a study comparing different learning methods (Delazer et al., 2005), training consisted either of learning by back-up strategies (learning by algorithm) or of learning by drill (rote learning of the result given two operands). At the time of testing, the two training sets were retrieved from memory and answered with comparable speed and accuracy. Items trained by drill were observed to activate more strongly the left angular gyrus than items trained by strategy, indicating that the left angular gyrus is particularly activated when the learning method (drill) encourages result retrieval. In a study comparing subtraction with multiplication (Ischebeck et al., 2006), both operations showed a similar decrease in activation within several frontal and parietal areas due to training, but only trained multiplication problems showed a significantly higher activation in the left angular gyrus than untrained problems. This indicates that training result retrieval was a more efficient strategy for multiplication than for subtraction problems.

Mathematical expertise, however, is not limited to the retrieval of arithmetic facts; it also encompasses procedural and conceptual knowledge. Procedural knowledge is the routine application of a sequence of steps prescribed by a stored algorithm to solve complex arithmetic problems such as, for example, multi-digit multiplication problems (McCloskey et al., 1985). It does not entail the making of inferences and may dissociate from conceptual knowledge (e.g., Cappelletti et al., 2001, 2005; Girelli and Delazer, 1996). To make inferences and to connect different pieces of information in arithmetic in a meaningful way, conceptual knowledge is needed. In arithmetic, conceptual knowledge entails a basic understanding of the operations and the arithmetic principles involved (see, for a review, Delazer, 2003). Several neuropsychological studies have provided evidence that conceptual knowledge may dissociate from arithmetic fact knowledge (e.g., Delazer and Benke, 1997; Delazer et al., 2006; Hittmair-Delazer et al., 1994, 1995) and from the knowledge of stored procedures and algorithms (Cappelletti et al., 2001, 2005; Girelli and Delazer, 1996). These studies suggest that at least partially separate neuronal networks might support overlearned fact knowledge, procedural knowledge and conceptual knowledge in arithmetic.

Transfer between arithmetic operations may rely on the insight that two arithmetic operations are related to each other, for example, that the result and operands of a multiplication problem represent the operands and result of a division problem. This insight is part of the conceptual knowledge of skilled users of arithmetic. However, transfer between operations may also rely on procedural knowledge. For example, students may have acquired the simple procedure of converting trained multiplication problems into division, without understanding the underlying arithmetic relations. In this case successful transfer between operations reflects procedural skills, but not conceptual understanding. In neuropsychological case studies it has been discussed whether divisions are separately stored in long-term memory (e.g., Cipolotti and de Lacy Costello, 1995) or answered by reference to related multiplication problems (e.g., Delazer et al., 2004; Girelli et al., 1996; Hittmair-Delazer et al., 1994). Behavioural learning studies with healthy subjects yielded somewhat conflicting results. Campbell (1997, 1999) as well as LeFevre and Morris (1999) reported highly correlated response times and error characteristics for multiplication and division. Moreover, on large division problems, participants reported that they 'recast' problems as multiplication (LeFevre and Morris, 1999). These findings suggest that at least the solution of difficult division problems involves access to multiplication. Little, if any transfer from multiplication training to division was observed by Rickard et al. (1994). In their identical elements model of arithmetic fact representation (Rickard et al., 1994; for a revised version, Rickard, 2005), complementary multiplication and division problems have independent representations, such that practice on one of these problems will not transfer to its complementary problem in the other operation (Rickard et al., 1994). The model proposes that for each triplet of numbers three independent fact representations are stored in memory (for example, $(4, 7, x) \rightarrow 28$; $(28/7) \rightarrow 4$; $(28/4) \rightarrow 7$). Only large division problems are not directly retrieved from memory representations. Instead, subjects use mediated fact retrieval and somehow reframe division problems as the corresponding multiplication to find out the answer (Rickard, 2005).

In the present study, we assessed the neural correlates of transfer between arithmetic operations, here, from multiplication to division. Participants trained on a set of ten complex multiplication problems for approximately 2 h on the day before scanning. Within the scanner, trained and untrained multiplication problems were presented. Similar to results from earlier studies (Delazer et al., 2003, 2005; Ischebeck et al., 2006, 2007), we expected a relative decrease in activation in frontal and parietal areas and a relative activation increase within the left angular gyrus due to training. Besides the multiplication problems, division problems were presented in the scanner as well. Division problems related to the trained multiplication problems (e.g., $138:3=?$ (46) is related to $46\times3=?$ (138)) represent the *transfer condition* and were compared with division problems that are not related to the trained multiplication problems (*no-transfer condition*). We hypothesized that participants might show faster reaction times and higher accuracy for related than for unrelated division problems. With regard to the changes in brain activation following learning, we expected less activation of frontal brain areas because related division problems solved by transfer should pose less demand on working memory and attention resources. Also, relatively less activation in intraparietal areas and more activation within the left angular gyrus might be expected for the related than for the unrelated division problems, if participants use the multiplication knowledge acquired during training to solve the related division problems. An additional aim of this study was to investigate the neural correlates of possible inter-individual differences in learning as well as in transfer. If behavioural learning and transfer effects differ between individuals, it can be expected that activation within the left angular gyrus might correlate with performance results.

Methods

Participants

Twenty-one right-handed healthy young adults participated in the fMRI experiment. All were students of the University of Innsbruck. They had normal or corrected-to-normal vision and no history of neurological or psychiatric illness. One participant had to be excluded from the analysis for failing to complete the training; three participants had to be excluded because of excessive motion (i.e., exceeding 4 mm translation, or 4° rotation). This left 17 participants (7 female, mean age 25 years/SD 2.2) for data analysis. All participants received monetary compensation and had given written informed consent. The study had been approved by the ethics committee of the Medical University Innsbruck.

Stimuli

In total, 50 multiplication problems of comparable difficulty were created for the experiment. All were two-digit times one-digit problems with three-digit solutions. Per participant, 10 problems out of these 50 were selected for training, yielding five randomizations. Untrained multiplication problems and division problems for the transfer (related) and no-transfer (unrelated) conditions were taken or generated from this pool of problems. This ensured that differences between trained and untrained multiplication problems or related and unrelated division problems were only due to training and not to differences between problems.

Procedure

Training preceded the fMRI session on the day before scanning (Fig. 1a). The training phase required participants to repeatedly solve ten multiplication problems. In total, each problem had to be solved 72 times. This number of repetitions ensured that performance was dominated by memory retrieval (Logan and Klapp, 1991). The training was done in a single session and lasted approximately 2 h. When a problem was presented, participants typed in the three-digit solution using the number pad of a computer keyboard. As training progressed, the maximum time allowed to type in the first digit of the solution was reduced systematically from 10 to 3 s (Repetitions 1–12: 10 s, Repetitions 13–24: 8 s, Repetitions 25–36: 6 s, Repetitions 37–48: 5 s, Repetitions 49–60: 4 s, Repetitions 61–72: 3 s). To discourage participants from entering the first digit before having completely calculated the solution, time was limited for the typing of the subsequent digits. After typing in the first digit of the solution, participants had 1.5 s (Repetitions 1–36) or 1 s (Repetitions 37–72) to type in each subsequent digit. Digits that were correctly and timely entered were displayed on the computer screen next to the equal sign of the problem (e.g., 46×3=_ _ _). Errors were not displayed. The problem remained visible until the correct solution was entered or until the time limit was reached. The completely correct solution remained visible on the computer screen for 1 s. Feedback was given after each trial. In case of an error or timeout with any digits, the trial was repeated until a correct and timely answer was received. A problem was only presented when participants indicated their readiness by key press, making it possible for them to pause between trials.

Behavioural tests were conducted before training (pre-training test), directly after training (post-training test) and after the scanning session (post-scanning test) to assess performance on trained and untrained multiplication problems as well as performance on related and unrelated division problems. Multiplication and division were tested separately. Trained (N=10×2) and untrained (N=20) multiplication problems were presented mixed, as were related (N=10×2) and unrelated (N=20) division problems. Related division problems were constructed on the basis of the trained multiplication problems. For example, a multiplication problem such as 17×7 (=119) was associated with the division problem 119 : 7 (=17). Division problems consisted of a three-digit dividend with a one-digit divisor and a two-digit solution. Division problems could be either related to the trained multiplication problems (transfer condition) or unrelated (no-transfer condition). For the pre- and post-training tests, as well as the post-scanning test, participants were required to type in the two-digit solution (division problems) or three-digit solution (multiplication problems) using the same procedure as in the first training phase (Repetitions 1–12). However, different from the training session, the solution was not displayed on the computer screen, no feedback was given and wrong/timeout trials were not repeated. The fMRI scanning session was conducted on the day after the training (see Fig. 1a).

In the fMRI experiment, problems of four conditions were realized: trained multiplication, untrained multiplication, related division, unrelated division. Different from the training and behavioural tests, participants were not required to type in the whole solution. Instead, a two-alternative-forced-choice task was used. Six seconds after presentation of the problem, two numbers, the solution and a distractor, were presented next to each other. Participants answered by pressing the button on the side of the solution (see Fig. 1b). The two-alternative-forced-choice task used here has been used in previous studies (Delazer et al., 2003, 2005; Ischebeck et al., 2006). Care was taken in the selection of distractors to prevent participants from recognizing distractors and from applying short-cut strategies (e.g., parity check, multiplying only the units). For the multiplication problems, distractors differed from the solution by ±10, or were related (±1 operand) to the first or the second operand. As an example, for a problem such as 46×3 (=138), a distractor related to the first operand could be (45×3=) 135 and a distractor related to the second operand could be (46×4=) 184. For the division problems, distractors differed from the solution by ±1 (see Table 1 for a summary of the main properties of the problems and distractors).

The experiment was realized as a block design. Activation blocks alternated with 30 s resting blocks (looking at a fixation cross). An activation block consisted of four trials of one of the four conditions (trained multiplication, untrained multiplication, related division, unrelated division) and had a duration of 30 s. A trial consisted of the presentation of the problem for 6 s, followed by the presentation of the two alternatives for 1.5 s, yielding a total trial duration of 7.5 s. Participants were instructed to avoid errors and to react as fast as possible. The 6 s presentation time of the problem before presenting the response alternatives was chosen to ensure that participants could complete the calculation for untrained problems. Each condition consisted of 40 trials, presented in a total of 10 blocks. Therefore, the four conditions of the experiment gave a total of 160 trials, or 40 blocks. All blocks of the experiment were administered in one session without break. The fMRI measurement consisted of one experimental

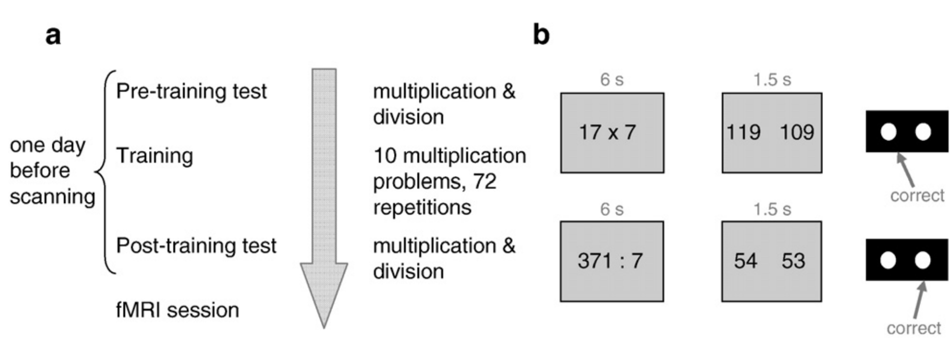

Fig. 1. Schematic illustration of the experiment and the task within the scanner. (a) Overview of the tests and the training before scanning. Participants had to type in the result. (b) Task within the scanner. Participants had to choose the correct alternative. Response times were measured from the onset of the presentation of the alternatives. Multiplication and division problems were presented in separate blocks of four problems each, alternating with 30 s fixation.

Table 1
Main properties of the stimulus sets

	First operand	Second operand	Correct solution	Distractor type	Parity congruency[a]	Distance from correct solution
Multiplication						
Trained	Range 14–97	Range 2–9	Range 111–480	±10	100.0%	
				±1' operand	50.0%	Range 2–9
				±2' operand	50.0%	Range 14–97
Untrained	Range 14–97	Range 2–9	Range 111–480	±10	100.0%	
				±1' operand	50.0%	Range 2–9
				±2' operand	50.0%	Range 14–97
Division						
Related	Range 111–480	Range 2–9	Range 14–97	±1	0%	
Unrelated	Range 111–480	Range 2–9	Range 14–97	±1	0%	

[a] Parity congruency between distractor and correct answer.

run taking approximately 40 min. To avoid that participants had to switch between operations, the two multiplication conditions (trained and untrained) were presented during the first half of the experiment and the two division conditions (related and unrelated) in the second half. Trained and untrained multiplication blocks were presented alternately, as were blocks with related and unrelated division problems. Participants were assigned to one of two block sequences to balance block order effects. Stimulus presentation, time measurement and scanner triggering were controlled by a computer outside the scanner room using in-house experimentation software. Synchronization between computer and scanner was verified using the timing information from the MR-image header data. The response recording device was based on optical signal transmission and was compatible with the MR environment. Stimuli were projected on a screen at the foot end of the scanner bed and viewed by the participant over a mirror mounted on top of the head coil. Small sand sacks were used within the head coil to reduce head motion. Participants wore ear plugs and headphones as protection against the scanner noise.

Behavioural data analysis

Only the data of the 17 participants that did not move excessively within the scanner were analyzed. Only correct trials (all digits correct) were entered into the analysis of reaction times (RTs). RT was the time between the presentation of the problem and the entering of the first digit of the solution by the participant. In each of the three tests (pre-/post-training and post-scanning test) there was a total of 1360 trials for all 17 participants. There was a total of 12.50%, 15.37%, 15.66% errors and 27.72%, 17.43%, 10.74% timeouts in the pre-/post-training and post-scanning test, respectively. For the analysis of the training data, mean RTs of trained multiplication problems were entered into a repeated-measure ANOVA with training phase (Repetitions 1–12, Repetitions 13–24, Repetitions 25–36, Repetitions 37–48, Repetitions 49–60, Repetitions 61–72) as within-subjects factor. For the pre- and post-training tests as well as for the post-scanning test, mean RTs were analyzed separately for multiplication and division problems by a repeated-measure one-way ANOVA with training (trained, untrained) and transfer (related, unrelated) as within-subjects factor, respectively. Error rates including wrong answers and timeouts were transformed using the $2\arcsin\sqrt{p}$ transformation (Bishop et al., 1975, pp. 367 ff) to achieve approximate variance equality before they were entered into a repeated-measures ANOVA similar to that for RTs.

(f)MRI data acquisition

(f)MRI measurement was performed with a 1.5 T Siemens Symphony scanner. A Siemens-issued bird-cage head-coil was used. For the functional images an EPI-sequence (TE = 60 ms, flip angle = 90°) sensitive to T2* contrast was run. The images had an in-plane spatial resolution of 3 mm (FOV = 192 mm, matrix = 64 × 64). For each image (TR = 3.0 s) 24 axial slices were acquired ascendingly and parallel to the AC–PC line with a thickness of 4 mm and 1 mm gap. Additionally, an anatomical scan (MPRAGE) was performed (TI = 1000 ms, TE = 3.93 ms, TR = 1670 ms, flip angle = 15°, matrix = 256 × 256, FOV = 220 mm, 112 slices, in-plane spatial resolution = 0.9 mm, 1.4 mm thickness).

(f)MRI data analysis

(f)MRI data analysis was performed with SPM2 (Wellcome Department of Cognitive Neurology, London, U.K.). The first four images of each functional series were discarded to ensure signal stabilization. The functional data of each participant were motion-corrected to the first image of the series. The structural image of each participant was registered to the time series of functional images and normalized using the T1 template provided by SPM2, corresponding approximately to Talairach and Tournoux (1988) Space (see also Brett et al., 2001; for a conversion algorithm of MNI coordinates to Talairach and Tournoux space, http://imaging.mrc-cbu.cam.ac.uk/imaging/MniTalairach). Here, we report all coordinates as given by SPM. The functional images were normalized using the normalization parameters of the structural image. Finally, the functional images were smoothed in the spatial domain using a Gaussian kernel of 9 mm FWHM. A statistical analysis on the basis of the general linear model was performed, as implemented in SPM2. The canonical form of the hemodynamic response function as given in SPM2 with its first time derivative was used to generate model time courses for the different conditions. As parameters for the modelling, block onsets were the presentation of the first problem of each block for each condition (trained multiplication, untrained multiplication, related division, unrelated division) and block duration was 32 s. The motion parameters were entered into the analysis as regressors of no interest. To control for possible brightness differences between scans due to a slight temporal variation in the computer controlled scanner triggering, the interval between two successive scans was entered into the model as a regressor of no interest. A high-pass filter (cut-off frequency: 1/500 Hz) was used to remove low frequency drifts. No global normalization was used. To realize a random effects model, the contrast images calculated for individual subjects were entered into a second level analysis (Friston et al., 1999). The resultant statistical parameter maps were thresholded using an initial uncorrected p-value threshold of less than 0.001, reporting only clusters as significant with a corrected p-value of less than 0.05 on cluster level. Anatomical labels are given on the basis of the classification of the AAL (automated anatomical labelling) atlas (Tzourio-Mazoyer et al., 2002). Due to incomplete coverage of the cerebellum that also depended on individual head size, cerebellar activations are not reported.

ROI-analysis

Two region of interest analyses (ROI) were performed. A first region of interest (ROI) within the left angular gyrus was defined on the basis of the AAL atlas (Tzourio-Mazoyer et al., 2002). For the ROI-analysis the Marsbar toolbox was used (M. Brett, http://marsbar.source forge.net). A second region ROI analysis was performed for activation values at the peak coordinate from the comparison between unrelated and related division problems. Effect sizes from the comparisons of each of the four conditions (trained/untrained multiplication problems, related/unrelated division problems) to baseline were averaged per participant for all voxels within the cluster. For the analysis of the ROI-data, effect sizes per participant and operation (multiplication, division) were entered into a repeated-measures analysis of variance (ANOVA) with the factor training/transfer (trained, untrained/related, unrelated). For the correlation analyses of the effect size values within the ROIs with behavioural results from the post-training test, an index was calculated to reflect individual training and transfer effects. This measure was calculated on the basis of the mean RTs as follows: for the training index, RTs to trained multiplication problems were subtracted from RTs to untrained multiplication problems, and divided by the mean RTs for multiplication problems to account for individual differences in mean RTs. Similarly, for the transfer index, RTs to related division problems were subtracted from RTs to unrelated division problems, and divided by the mean RTs for division problems. The construction of these indices entails that positive values denote a training or transfer effect, with reaction times to trained or related problems being smaller than reaction times to untrained or unrelated problems. These two measures (training multiplication, transfer to division) were then correlated to the mean activation values within the two ROIs (left angular gyrus, peak coordinate).

Results

Behavioural results

Training phase

RTs and error rates decreased monotonously over the six phases of the training with each phase consisting of 12 repetitions of each problem (see Table 2). The training effect was significant for RTs ($F(5, 80)=86.39$, $p<.001$) as well as for error rates ($F(5, 80)=3.96$, $p<.01$).

Pre-training, post-training and post-scanning tests

In the pre-training test, there was no significant difference between to-be-trained and untrained multiplication problems (RTs: $F(1, 16)=2.75$, $p=.12$; errors: $F(1, 16)=2.48$, $p=.135$) as well as between related and unrelated division problems (RTs: $F(1, 16)=.00$, $p=.96$; errors: $F(1, 16)=2.51$, $p=.133$). Multiplication problems that were to be trained later (trained multiplication; mean RT 5315 ms/SD 1025; mean error rate 29.18%/SD 21.95) were answered as fast and as accurately as untrained problems (mean RT 5609 ms/SD 1132; mean error rate 33.82%/SD 18.92). The same was true for related division problems (mean RT 5285 ms/SD 1561; mean error rate 46.47%/SD 28.93) and unrelated division problems (mean RT 5274 ms/SD 1633; mean error rate 51.47%/SD 26.68).

In the post-training test, there was a significant main effect of training for multiplication ($F(1, 16)=87.60$, $p<.001$) with trained problems being answered faster than untrained problems (trained: 2839 ms/SD 910, untrained: 5196 ms/SD 1174). There was no significant transfer effect in division (related: 4834 ms/SD 1633, unrelated: 4945 ms/SD 1403; $F(1, 16)=.12$, $p=.728$). In the analysis of the error rates, less errors were made with trained multiplication

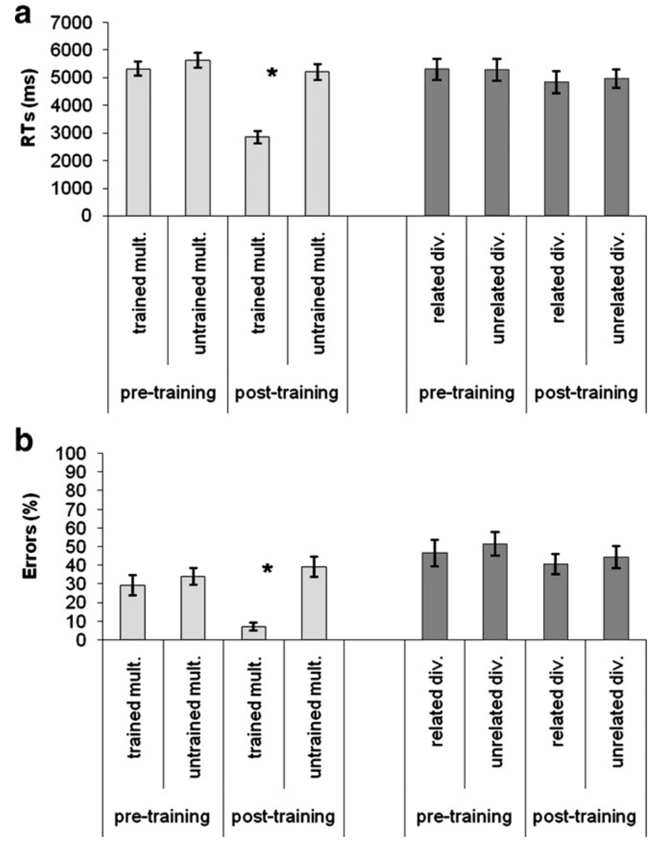

Fig. 2. Behavioural results for the pre- and post-training tests. Reaction times for multiplication and division problems are given in (a), error rates in (b). Error bars denote the standard error of the mean. The asterisks indicate the significant differences (trained versus untrained multiplication at post-training: both $p<.0001$).

problems than with untrained problems (trained: 7.06%/SD 8.49, untrained: 39.12%/SD 21.60), which is reflected in a significant main effect of training ($F(1, 16)=82.29$, $p<.001$). The effect of transfer in division was not significant (related: 40.59%/SD 22.35, unrelated: 44.41%/SD 24.17; $F(1, 16)=.18$, $p=.193$). RTs and error rates for both tests are also represented in Fig. 2.

In the post-scanning test, all effects were significant in RTs (trained: 2933 ms/SD 823, untrained: 4652 ms/SD 1034, effect of training: $F(1, 16)=91.46$, $p<.0001$; related: 4144 ms/SD 1543, unrelated: 4721 ms/SD 1278, effect of transfer: $F(1, 16)=5.02$, $p<.05$). In error rates, there was a significant effect of training (trained: 9.12%/SD 9.05, untrained: 37.06%/SD 21.51; $F(1, 16)=35.44$, $p<.0001$), while the effect of transfer did not reach significance (related: 26.76%/SD 19.60, unrelated: 32.65%/SD 22.44; $F(1, 16)=2.05$, $p=.171$). For RTs as well as error rates, there was a significant difference between related division and trained multiplication problems (both $p<0.001$, Newman–Keuls post-hoc tests), but no difference between unrelated division and untrained multiplication problems.

Table 2
Reaction times and error rates during the training phase ($N=17$)

Training phase	1	2	3	4	5	6
RT in ms	3513	2591	2215	1980	1765	1501
	(1774)	(1399)	(1160)	(935)	(779)	(561)
ER in %	17.3	11.3	10.1	10.4	9.7	14.8
	(12.4)	(9.3)	(8.0)	(8.9)	(9.5)	(15.4)

Each phase comprises 12 repetitions of each of the ten multiplication problems. RT=reaction times, ER=error rates. Standard deviations are given in brackets.

Table 3
Reaction times and error rates during the scanning session ($N=13$, the data of four out of 17 participants could not be analyzed due to response box malfunction)

Operation	Multiplication		Division	
Training/transfer	Untrained	Trained	Unrelated	Related
RT in ms	831	765	767	717
SD	(90)	(104)	(117)	(115)
ER in %	16.5	7.9	23.5	16.5
SD	(13.2)	(11.6)	(22.3)	(17.8)

RT=reaction times, ER=error rates. Standard deviations are given in brackets.

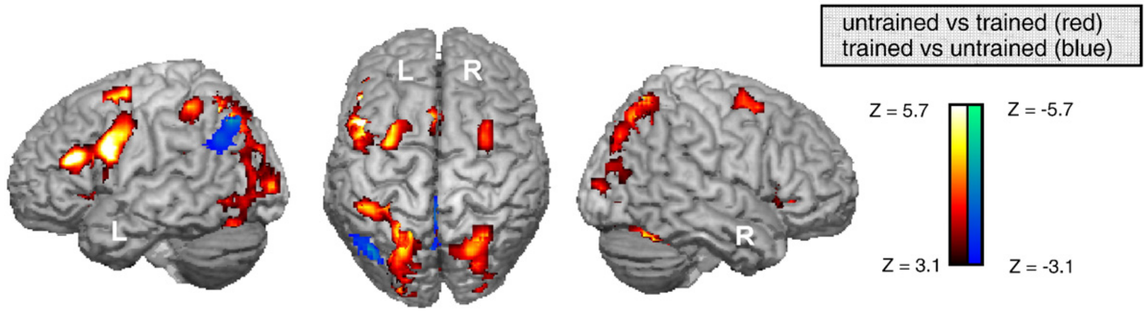

Fig. 3. Significant activation differences in the contrasts untrained > trained and trained > untrained. Threshold: p < .001 uncorrected, showing only clusters with a corrected p-value on cluster level of p < .05.

Behavioural results within the scanner

The data of four out of 17 participants could not be analyzed due to response box malfunction. In RTs, there was a significant main effect of training for multiplication (F(1, 12) = 10.43, p < .01) with trained problems being answered faster than untrained problems (see Table 3 for means and standard deviations). There was also a transfer effect in division (F(1, 12) = 4.81, p = .05). In the analysis of error rates, less errors were made on trained multiplication problems than on untrained problems, which is reflected in a significant main effect of training (F(1, 16) = 37.53, p < .001). The effect of transfer in division was also significant (F(1, 12) = 8.64, p < .05). It should be noted that RT measurement started with the presentation of the response alternatives, that is, 6 s after the presentation of the problem.

fMRI results

Analysis of the training and transfer effects

When untrained multiplication problems were compared with trained multiplication problems (Fig. 3, Table 4), significant activation differences were observed within a range of frontal areas, such as the

Table 4
Imaging results for the training effect in multiplication, the transfer effect to division, as well as the differences between multiplication and division

Side		x	y	z	k	Z		x	y	z	k	Z
		Multiplication: untrained > trained						Multiplication: trained > untrained				
Frontal												
Left	IFG	−42	9	24	1615	5.70						
Left	Insula	−24	18	3	1615[a]	5.05						
Left	SMA	−6	−15	51	1615[a]	4.88						
Left	MFG	−30	6	57	1615	4.80						
Right	Insula	30	30	6	163	4.35						
Right	MFG	45	39	15	58	4.27						
Right	MFG, SFG	30	9	57	110	4.27						
Basal ganglia												
Left	Caudate	−18	−3	18	110[a]	4.73						
Right	Caudate	18	3	21	110	4.40						
Right	Thalamus	24	−30	6	42	3.86						
Parietal												
Left	SPL, IPL	−24	−57	51	2557	5.38	AngG	−45	−69	45	120	4.50
Left							PC, precuneus	−9	−48	33	274	4.18
Right	PostG, IPL	48	−33	51	60	4.09						
Right	SPL, SOG	24	−63	63	671	4.58						
Right	SPL	18	−69	51	671[a]	4.51						
Occipital												
Left	MOG	−21	−87	3	2557[a]	5.10						
Left	MOG	−30	−69	30	2557[a]	4.73						
Left	IOG	−33	−69	−6	2557[a]	4.99						
		Transfer to division: unrelated > related						Transfer to division: related > unrelated				
	Ns						Ns					
		Differences: division > multiplication						Differences: multiplication > division				
Temporal												
Right	MTG	57	−48	−9	56	3.85	Ns					
Parietal												
Left	MOG, IPL	−33	−78	39	70	4.94						

Initial threshold: p < .001 uncorrected, p < .05 corrected on cluster level. Coordinates are reported as given by SPM2 (MNI space) and correspond only approximately to Talairach and Tournoux space. The first label denotes the location of the maximum, the following labels denote further areas containing a majority of voxels of the activated cluster. Abbreviations: k = cluster size, Z = Z-value, IFG = inferior frontal gyrus, MFG = middle frontal gyrus, SFG = superior frontal gyrus, SMA = supplemental motor area, PostG = postcentral gyrus, SPL = superior parietal lobule, IPL = inferior parietal lobule, AngG = angular gyrus, PC = posterior cingulate gyrus, MTG = middle temporal gyrus, IOG = inferior occipital gyrus, MOG = middle occipital gyrus, SOG = superior occipital gyrus.

[a] Activation is part of a bigger cluster.

supplemental motor area, the insula and the middle frontal gyrus bilaterally, the left inferior frontal gyrus and the right superior frontal gyrus. Activation differences were also observed within the superior and inferior parietal lobule including the intraparietal sulcus, bilaterally. Further activations were observed within the caudate nuclei of the basal ganglia and the left middle occipital gyrus. When trained multiplication problems were compared with untrained multiplication problems, significant activation differences were obtained within the left angular gyrus and the posterior cingulate/precuneus.

To investigate a possible transfer effect from multiplication to division, division problems that were related to the trained multiplication problems were compared with unrelated division problems. There was no significant activation difference when unrelated division problems were compared with related division problems, or when related division problems were compared with unrelated division problems. When the initial threshold was lowered to $p<0.005$ uncorrected in order to avoid missing potentially meaningful activation, an activation within the left angular gyrus obtained significance in the comparison of related versus unrelated division problems (coordinates: −39 −69 51, $p<.05$ corrected, on cluster level).

To evaluate activation levels for transfer and training within the left angular gyrus, an ROI analysis was conducted. This analysis was calculated by entering the averaged effect sizes per participant and operation (multiplication, division) into an ANOVA with the factor training/transfer (trained/related vs. untrained/unrelated). This analysis was calculated for an ROI of the left angular gyrus as well as for the effect sizes at the peak coordinates for the transfer effect (−39 −69 51). For multiplication, a significant main effect of training ($F(1, 16)=31.76$, $p<.001$, for the peak coordinates: ($F(1, 16)=6.22$, $p<.05$) was observed. For division, a significant main effect of transfer ($F(1, 16)=19.80$, $p<.001$, for the peak coordinates: ($F(1, 16)=16.38$, $p<.001$) was also observed. These analyses indicate that the left angular gyrus shows a training effect for multiplication as well as a transfer effect for division. Average effect sizes from this ROI analysis and for the peak coordinate are given in Fig. 4.

Differences between operations

To compare potential differences between operations, independent of training or transfer effects, untrained multiplication problems were compared with unrelated division problems. Untrained multiplication problems did not activate any brain area more strongly than unrelated division problems. In the reverse comparison, significant activation differences were observed within the right middle temporal gyrus and in the left inferior parietal lobule (see Table 4).

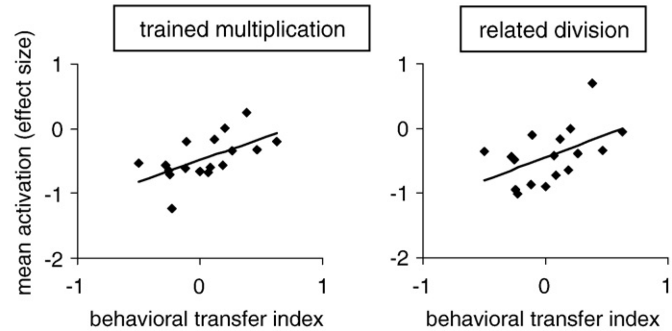

Fig. 5. Correlations between the behavioural transfer index and activation within the left angular gyrus for trained multiplication and related division problems.

Individual differences with regard to training and transfer

To investigate whether additional factors such as inter-individual differences modulate the transfer effect within the left angular gyrus in division, correlations were calculated between the activation for the left angular gyrus ROI and at the coordinate −39 −69 51 for the four conditions, separately, and two behavioural measures, namely, the transfer and training indices, from the post-training test. The two indices were not significantly correlated. Inter-correlations between the activation values for the left angular gyrus and the peak coordinate were all significant ($p<.01$). However, only two correlations between activation values and behavioural measures were significant: there was a significant correlation between the transfer index and activation within the left angular gyrus for trained multiplication ($r=.60$, $p<.05$) and for related division ($r=.50$, $p<.05$; Fig. 5). No significant correlations were observed for the training index. It should be noted that differences in activation between trained and untrained problems as well as between related and unrelated problems, within the left angular gyrus ROI as well as at the peak coordinate, did not correlate significantly with any of the two indices. This indicates that the level of increase in activation within the left angular gyrus for the training and transfer condition is elevated in individuals that show a transfer effect in reaction times.

Discussion

While previous brain imaging studies on learning arithmetic mostly investigated effects for the arithmetic operation that was trained, the present study explored the possibility of transfer between

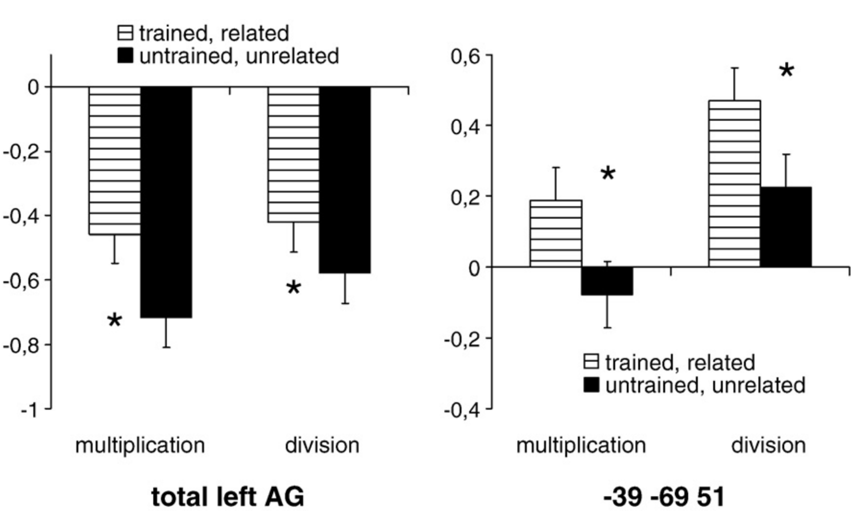

Fig. 4. Activation averaged over the left angular gyrus ROI and at the coordinate −39 −69 51 for all four conditions (trained multiplication, untrained multiplication, related division, unrelated division). Error bars denote the standard errors of the mean.

operations. A set of ten complex multiplication problems was trained extensively by problem repetition on the day before scanning. Before and after the two-hour training session, a short behavioural test was conducted to assess training effects and possible transfer from multiplication to division. Within the scanner, trained and untrained multiplication problems were presented as well as division problems that were related or unrelated to the trained multiplication problems. We will first discuss results related to the training effect for multiplication, then results related to the transfer effect to division problems, and finally we will refer to the effect of inter-individual differences.

Training effect for multiplication

After training, the behavioural results showed faster reaction times and smaller error rates for trained multiplication problems as compared with untrained multiplication problems. In the fMRI results, similar to previous studies, stronger activation in several frontal and parietal areas was observed for untrained as compared with trained multiplication problems. When trained multiplication problems were compared with untrained multiplication problems, relatively stronger activation was observed within the left angular gyrus. These results replicate findings of previous imaging studies investigating the learning of complex multiplication problems (Delazer et al., 2003, 2005; Ischebeck et al., 2006, 2007). The observed activation decreases in several frontal and parietal areas (including the intraparietal sulcus) and the relative activation increase within the left angular gyrus was interpreted as indicating a shift from calculation processes to result retrieval. Complex multiplication involving multi-digit operands requires a sequence of steps to get to the correct solution and strongly relies on working memory resources. Stronger activations in frontal areas such as the prefrontal and inferior frontal gyrus, as well as in areas within the inferior and superior parietal lobule including the intraparietal sulcus have been observed when complex arithmetic problems were compared with simple problems (Gruber et al., 2001; Kong et al., 2005; Menon et al., 2000; Stanescu-Cosson et al., 2000; Zago et al., 2001) or when calculation problems were compared with control tasks with digits such as, for example, counting (Gruber et al., 2001; Hayashi et al., 2000; Rickard et al., 2000; Rueckert et al., 1996; Zago and Tzourio-Mazoyer, 2002). When a problem is solved repeatedly, however, the participant is likely to remember the result from earlier presentations and can do this without some or all of the intermediate processing steps required for its solution by calculation. The systematic change in activation patterns observed here, consisting in an activation decrease in some brain areas as well as an activation increase in other brain areas might indicate the development of new cognitive processes or representations by learning or a change in the degree to which processing components involved in a task are engaged (Poldrack, 2000). In line with previous studies (Delazer et al., 2003, 2005; Ischebeck et al., 2006, 2007) the observed change in activation patterns seems to indicate a shift from calculation to result retrieval for the repeated problems due to learning.

The results of the present study also show an area within the posterior cingulate gyrus/precuneus that was more strongly activated in trained as compared with untrained problems. A similar activation (with a slightly superior focus) was found in a previous study comparing the effects of different training methods (Delazer et al., 2005). Contrasting learning by drill and learning by strategy, a large bilateral activation including the precuneus and extending to the left angular gyrus was significant. In the reverse contrast – strategy versus drill – a more inferior activation including the precuneus appeared. Thus, the activation found in the present study is compatible with memory based retrieval of arithmetic results and has been previously described in association with left angular gyrus activation. Activation of the precuneus has also been described in tasks of episodic memory retrieval (e.g., Cabeza et al., 2003; for a review, Cabeza and Nyberg, 2000). It is conceivable that episodic memory might have contributed to the arithmetic learning effects observed here. Furthermore, a relative increase in neural activity associated with familiarity of faces and voices in the posterior cingulate cortex was reported (Shah et al., 2001). The activation observed in the posterior cingulate gyrus/precuneus might therefore also be due to the familiarity of the trained items.

Transfer effect for division

To evaluate a possible transfer from multiplication to division, we compared division problems related to trained multiplication with unrelated division problems. Overall, no significant differences were observed, neither behaviourally (post-training test) nor in the whole brain analysis of the imaging data. It is possible that the two-hour training period conducted here was too short or that the complex multiplication problems with three-digit solutions used for training were too difficult to allow an efficient transfer from multiplication to division. Another possibility is that the intermixed presentation of trained (related) and untrained (unrelated) problems in the post-training test made transfer between operations difficult. In the intermixed presentation participants might have had difficulties to recognize problems as familiar (trained, related) or unfamiliar (untrained, unrelated). They might have chosen not to apply different approaches (retrieval, transfer, calculation), but could have preferred calculation for all conditions. Consequently, blocked presentation during the scanning session might have facilitated transfer.

A transfer effect emerged when the analysis of the imaging data was restricted to brain areas previously observed to show specific sensitivity to arithmetic facts training, namely the left angular gyrus. The observation of a significant transfer effect within the left angular gyrus, a brain area involved in the retrieval of arithmetic facts, suggests that newly acquired fact knowledge was – at least to some extent – recruited for the solution of unknown division problems. The newly acquired fact knowledge might have either been used directly in finding the solution for the related division problem, or it was used to check the correctness of the division result in a subsequent step. Although we cannot clearly decide between both possibilities, the finding that division is not generally significantly slower than multiplication makes a two-step procedure unlikely. The increase in activation evidenced by the ROI analysis indicates that fact retrieval involving the left angular gyrus was indeed involved in answering related division. These findings are in agreement with behavioural studies showing that large division problems are solved by reframing them as multiplication problems and by using multiplication fact knowledge (LeFevre & Morris, 1999; Mauro, LeFevre, & Morris, 2003). In the case of large and unpracticed division problems as used in the present investigation, decomposition is also assumed in models that posit independent fact representations for corresponding multiplication and division (Rickard, 2005).

Individual differences

Finally, the present study explored whether transfer is related to individual performance. It is possible that the conceptual understanding and/or the procedural knowledge required for transfer was not equally available to all individuals tested. Inter-individual differences in behavioural measures might co-vary with brain activation patterns. Grabner et al., (2007) showed that individuals with higher mathematical competence displayed stronger activation in the left angular gyrus than less competent individuals, while answering single-digit and multi-digit multiplication problems. The study suggests that individual differences in mathematical competence are accompanied by brain activation differences in an area related to the retrieval of arithmetic fact knowledge. This finding was interpreted as mathematically more competent individuals showing a stronger reliance on retrieval processes in multiplication than less competent individuals. Based on these findings, we had hypothesized that individual differences in behavioural measures (overall reaction time, error rates, transfer and training effects) could be associated with activation differences within the left angular gyrus. A significant correlation was observed specifically for the behavioural transfer effect and the activation within the left angular gyrus for trained multiplication and related division problems. It could be speculated that mathematically more competent individuals showed more transfer by relying more on arithmetic fact retrieval, likely to be mediated by the left angular gyrus, than less competent individuals. Interestingly, significant inter-individual correlations were only observed between the transfer index and brain activation in the training and transfer conditions. This confirms the interpretation that the activation within left angular gyrus is specifically involved in arithmetic fact retrieval and skilled mathematical performance. It should also be noted that a correlation was only found for the transfer index and not for the training index. Transfer and training indices were also not significantly correlated. It is possible that inter-individual differences disappeared in training due to a ceiling effect. The two-hour training might have been extensive enough for multiplication, so that all participants profited similarly from training, thereby attenuating inter-individual differences. However, training might have been too short to have allowed all individuals to use the acquired knowledge equally successfully for transfer. It is possible that a longer training might have yielded stable transfer effects in all participants.

In conclusion, the present study yielded some evidence that successful transfer of knowledge between arithmetic operations is accompanied by modifications of brain activation patterns. The importance of the left angular gyrus for arithmetic fact retrieval was also confirmed. However, it is unclear in how far the individual differences observed in transfer are related to the duration of the training. Future studies with longer training periods might find that more efficient retrieval of newly acquired knowledge facilitates transfer to a new operation in all participants. For a deeper understanding of transfer, especially of the conceptual understanding and procedural knowledge involved, further experimental investigations are needed.

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