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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., 19×4=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) →28; (28/7) → 4; (28/4) →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 × 3 = ? (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