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Learning by strategies and learning by drill—evidence from an fMRI study

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The present fMRI study investigates, first, whether learning new arithmetic operations is reflected by changing cerebral activation patterns, and second, whether different learning methods lead to differential modifications of brain activation. In a controlled design, subjects were trained over a week on two new complex arithmetic operations, one operation trained by the application of back-up strategies, i.e., a sequence of arithmetic operations, the other by drill, i.e., by learning the association between the operands and the result. In the following fMRI session, new untrained items, items trained by strategy and items trained by drill, were assessed using an event-related design. Untrained items as compared to trained showed large bilateral parietal activations, with the focus of activation along the right intraparietal sulcus. Further foci of activation were found in both inferior frontal gyri. The reverse contrast, trained vs. untrained, showed a more focused activation pattern with activation in both angular gyri. As suggested by the specific activation patterns, newly acquired expertise was implemented in previously existing networks of arithmetic processing and memory. Comparisons between drill and strategy conditions suggest that successful retrieval was associated with different brain activation patterns reflecting the underlying learning methods. While the drill condition more strongly activated medial parietal regions extending to the left angular gyrus, the strategy condition was associated to the activation of the precuneus which may be accounted for by visual imagery in memory retrieval.

Keywords: fMRI; Strategies; Drill

Introduction

Skilled and automatic performance in various cognitive tasks, for instance, reading, object recognition, orientation discrimination, and arithmetic fact retrieval, can be achieved by different learning strategies. Given sufficient training, various approaches, such as rote learning, executing algorithms, or back-up strategies, as well as active discovery and problem solving, may guide to expertise routine. In several domains, acquisition of new expertise is reflected by a shift from slow and step-by-step computation to fast and effortless processing, as well as by a lower error rate. Thus, behavioral measures, i.e., an increase in velocity and a decrease in error rates, as well as the successful transfer to unknown problems are commonly taken as correlates of successful learning. In recent years, brain imaging studies allowed to go beyond these behavioral measures and to track the cerebral activation patterns underlying the learning process (e.g., Poldrack, 2000). The present study aims to investigate the effects of two different learning methods, learning by strategy, i.e., applying a sequence of arithmetic operations, and learning by drill, i.e., learning to associate a specific result with two operands. Behavioral measures (reaction times, accuracy, transfer) as well as cerebral activation patterns related to the two learning methods are assessed. It is investigated whether expertise acquired by rote learning or by strategies is associated with specific modifications of cerebral activation patterns during the performance of an arithmetic task.

Most researchers agree on the aim of mathematical instruction, i.e., to achieve reliable, easily accessible, well-connected, meaningful, flexible, and adaptive knowledge, but there is little agreement with regard to the teaching methods to achieve this goal. Research on mathematics instruction puts either emphasis on skill learning and memory retrieval or on conceptual understanding and active problem solving (Baroody, 2003). In the present study, we will focus on one aspect of arithmetic learning only, i.e., the

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acquisition of memorized facts. The motivation of this study was twofold—first, simple arithmetic is an ideal field to study the acquisition of new expertise, since learning conditions and learning contents can be easily defined. Second, the acquisition of arithmetic facts is of crucial importance for young students, as well as for patients after acquired brain damage. In fact, deficits in simple calculation are a frequent consequence of brain damage (Jackson and Warrington, 1986) and better knowledge about learning processes and rehabilitation is needed (Domahs and Delazer, in press; Girelli and Seron, 2001; Lochy et al., 2004).

Over the last years, wide agreement has been achieved that arithmetic expertise requires the interplay of different types of knowledge and that number processing and calculation are modularly organized. Regarding calculation, declarative knowledge of simple, overlearned arithmetic facts (knowing that 3 × 3 gives 9) may be distinguished from procedural knowledge (knowing how to multiply 34 × 67) and from conceptual knowledge (knowing that 3 × 18 equals 18 × 3). This very broad modular organization of arithmetic knowledge has been confirmed by not only several neuropsychological case studies with adults after acquired brain lesions (Cipolotti and de Lacy Costello, 1995; Dagenbach and McCloskey, 1992; Dehaene and Cohen, 1997; Delazer and Benke, 1997; Lampl et al., 1994; McCloskey, 1992; McCloskey et al., 1985; McNeil and Warrington, 1994; Pesenti et al., 1994; Sokol et al., 1991; Van Harskamp and Cipolotti, 2001), but also in some cases of developmental dyscalculia (Temple, 1991). Importantly, case studies demonstrated double dissociations between arithmetic fact knowledge on one hand and the execution of back-up strategies on the other hand (Dehaene and Cohen, 1997; Delazer and Benke, 1997; Hittmair-Delazer et al., 1994; Sokol and McCloskey, 1991; Sokol et al., 1989). Thus, neuropsychological investigations show that arithmetic fact knowledge may be accessed either from a long-term memory store or may be elaborated by back-up strategies; moreover, they suggest that these two pathways are separately implemented in the human brain.

Developmental studies (Barrouillet and Fayol, 1998; Lemaire and Siegler, 1995; Siegler, 1988) as well as experimental studies with adults (Anderson et al., 1999; Logan, 1988; Logan and Klapp, 1991; Rickard, 2004) converge on the view that the acquisition of arithmetic expertise is reflected by a shift from slow and effortful back-up strategies to skilled and fast retrieval from memory (but see for a different view Baroody, 1983, 1994, 1999). However, there is evidence that adults do not systematically retrieve answers to all simple addition or multiplication problems from long-term memory, but still apply a variety of back-up strategies even in problems with one-digit operands (Campbell and Timm, 2000; Campbell and Xue, 2001; Campbell et al., 2004; Geary and Wiley, 1991; Geary et al., 1993; Kirk and Ashcraft, 2001; LeFevre and Morris, 1999; LeFevre et al., 1996a,b). Whether memory retrieval and arithmetic back-up strategies are applied in parallel on a particular item or whether they exclude each other is under debate. One group of models assumes that retrieval and back-up strategies are accessed concurrently and that the faster process wins the race (Ashcraft, 1992; Logan, 1988; Wenger, 1999). Other models propose that either retrieval or a strategy is used (Barrouillet and Fayol, 1998; Lemaire and Siegler, 1995; Rickard, 2004; Siegler, 1988).

While most learning studies with adults used repetition and rote learning as training method, others compared learning by algorithms and learning by rote (Logan and Klapp, 1991). Both training methods (by rote and by algorithm) lead to skilled performance and reached the same automaticity criterion (i.e., a zero-slope increment as a function of the addend size) after approximately 60 presentations of each fact. From the body of cognitive experimental studies, the following conclusions can be drawn for the present investigation: performance shifts from algorithms to memory retrieval as training proceeds, the shift from algorithms to retrieval is item specific, and retrieval is the dominant process in skilled subjects. Finally, different training methods may lead to skilled performance and automatic retrieval.

Evidence on the neuroanatomical structures underlying the acquisition of arithmetic skills is scarce. A study (Pauli et al., 1994) using event-related potentials (ERPs) assessed training effects in simple calculation. Importantly, with increasing automaticity, fronto-central positivity diminished from session to session and the focus of positivity centered at centro-parietal regions. This shift reflected the learning effect with deliberate, conscious calculation in the first sessions and fast retrieval from memory in the last. Calculation strategies and algorithms relied more on fronto-executive functions allocating resources and organizing the processing stages of the task than highly automatized retrieval. A recent fMRI study (Delazer et al., 2003) allowed a more fine-grained assessment of activation patterns related to the acquisition of arithmetic knowledge. Contrasting untrained vs. trained items, the left intraparietal sulcus showed significant activation, as well as the inferior parietal lobule. These activations were interpreted as processing of quantities and non-automatized calculation (Burbaud et al., 1999; Chochon et al., 1999; Pesenti et al., 2000; Rickard et al., 2000). Furthermore, the untrained condition showed a significant activation in the left inferior frontal gyrus which was accounted for by higher working memory demands in the untrained condition. Contrasting the trained vs. the untrained condition, a significant focus of activation was found in the left angular gyrus, which mediates exact and highly automatized calculation, in particular simple multiplication facts (Chochon et al., 1999; Duffau et al., 2002; Lee, 2000). Thus, the shift of activation observed in the learning experiment (Delazer et al., 2003) from the intraparietal sulcus to the left angular gyrus reflects the modification from quantity based processing to more automatic retrieval. Overall, the study showed that relatively short training may lead to significant changes in cerebral activation patters.

Predictions for the present study

The study focuses on two main issues, the effect of training (comparing new and trained items based on the same algorithm) and the effect of different training methods (comparing items learned by different methods). Regarding the first issue, the following predictions can be made: if training leads to a modification of cognitive processes, i.e., from step-by-step algorithms to fast retrieval, untrained items as compared to trained items show more activation in areas subserving working memory functions, planning, and rule-based processing. Furthermore, we expect activation in areas relevant for quantity processing and non-automatized calculation, i.e., in the bilateral intraparietal sulci. Trained items as compared to untrained ones should show higher activation in areas subserving the retrieval of overlearned facts, in particular in the angular gyrus.

Regarding the second issue, the comparison of learning methods, two alternatives may be tested. Given the high number of repetitions ($n = 90$) for both methods, one may assume that both sets reach a high level of automaticity, that both are answered by