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Neural circuits involved in mental arithmetic: Evidence from Customized Arithmetic Training

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A thesis submitted in partial fulfillment of the requirements for the degree in Doctor of Philosophy

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by

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Abstract

An arithmetic training study was conducted using a novel paradigm known as Customized Arithmetic Training (CAT). Using the CAT system, self-reports obtained from the participants were used to generate individually tailored problem sets. These problem sets balanced strategy use such that each participant started with an equal amount of problems solved by fact retrieval (e.g., 2 + 2 = 4) and an equal amount of problems solved by procedural calculation (e.g., 34 + 37). Following the training period, participants solved trained and untrained problems from their customized arithmetic sets while undergoing an fMRI scan, after which they again provided self-reported strategy.

Through the use of the CAT paradigm, which tracks (for the first time) arithmetic strategy both pre- and post-training, the neural correlates of arithmetic learning were examined by separating calculated problems which became memorized through training from problems that were rehearsed but did not show a shift in strategy. This analysis produced results consistent with previous studies of arithmetic training, namely a shift from widespread fronto-parietal activation to focal activation of the angular gyrus. However, it also produced several novel findings relating to neural correlates of mental arithmetic, namely an association between right anterior hippocampus in fact retrieval as well as evidence of a temporal gradient which affected brain activity when comparing new vs old arithmetic facts. Furthermore, analysis of training effects on calculated problems (which did not become memorized) revealed a modulation of activity in the putamen, a structure commonly associated with the procedural memory system.

Keywords

Numerical Cognition, Episodic Memory, Procedural Memory, Training, Mental Arithmetic, fMRI, Neuroimaging, Cognitive Neuroscience

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Dedication

To my parents, Richard and Andrea. Thanks for all the love and support all these years.

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Chapter 1

1 Introduction to the study of mental arithmetic

Proficiency with formal mathematics is one of the prerequisites for successful participation in modern society. Low math skills are related to an increased likelihood of unemployment, physical illness, depression, and even arrest (Parsons & Bynner, 2005). Proficiency with math has also been shown to be beneficial for both healthcare workers and patients in terms of interpreting appropriate dosages of medication and understanding health-related statistics (Golbeck, Ahlers-Schmidt, Paschal, & Dismuke, 2005). Given the importance of numeracy and basic math for everyday life, it is important to study what gives rise to individual differences in mathematical ability. Recently, neuroscience methods have been used to explain these processes, and these explanations can help constrain current theories on math education, leading to more efficient educational programs. The work described in this dissertation focuses on how differences in training and strategy use affect the neural correlates of mental arithmetic. In doing so it describes the dynamic nature of the neural systems and cognitive processes that are involved in mental arithmetic, a consideration which is currently absent from neural models of number processing.

In terms of the neuroscience of numerical abilities there has been a long association between numerical skills and the parietal cortex, beginning with neuropsychological work in the early 20th century (e.g. Henschen, 1919). Later, research singled out the angular gyrus (AG), a structure within the ventral parietal cortex, as being important for calculation, as lesions to the AG resulted in deficits in this and other domains such as finger gnosis and the ability to write(Gerstmann, 1940). The first functional neuroimaging study of mental calculation also supported this finding. Specifically, Xe intra-carotid imaging revealed that blood flow increased in the bilateral AG and prefrontal region (Roland & Friberg, 1985). While these findings showed that both parietal and prefrontal cortices have important links to the ability to perform calculation, there was a large amount of variability in the activation patterns in these regions, no doubt in part due to the different methods and experimental contexts used to study these processes. For instance, some studies have reported activation of superior regions of the parietal lobe such as the intraparietal sulcus (IPS)(Dehaene et al., 1996; Rickard et al., 2000) and superior parietal lobe during calculation, while others have reported activation of the AG (Roland & Friberg, 1985; Rueckert et al., 1996). Despite this variability, a model explaining the neural basis of mathematical skill based on this and other data has emerged and has been influential in guiding research on the neural correlates of numerical and mathematical skills.

1.1 Models of mental arithmetic

The most widely cited theoretical account for explaining human mathematical skill is the 'triple-code' model (Dehaene & Cohen, 1995; Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999). This model gets its name from its prediction that numbers are processed in three formats; a visual code, which stores visual number symbols such as Arabic digits, a verbal code, in which arithmetic facts are stored, and an analog magnitude code, which would be used to judge whether one number is larger or smaller than another. Each of these codes requires a different processing stream. The visual code is associated with activity in the bilateral interior ventral occipito-temporal areas, while the verbal codes are associated with activity in the left perisylvian areas. Finally, the magnitude code is associated with activity in the bilateral IPS. According to this model, solving a visually-presented addition problem (such as 2 + 3) would first require the transcoding of the operands from the visual code into the verbal code (two plus three). The verbal code would then be used to retrieve the memory (5), a process that draws on a left-lateralized corticostriatal loop consisting of the thalamus, basal ganglia, and left angular gyrus (Dehaene & Cohen, 1997). For a more difficult addition problem that could not be solved through retrieval of the solution from memory (such as 25 + 28), additional semantic manipulations would need to be performed (such as converting the 28 to a 25, retrieving the solution to 25+25 and then finally adding the remaining 3). These semantic manipulations are associated with activity in the inferior parietal areas (the magnitude code) such as the inferior parietal sulcus (IPS). The selection of the appropriate manipulations (e.g., strategy and planning) are associated with activity in the prefrontal regions, and the attentional demands (both spatial and non-spatial) involved in calculation are associated with activity in the superior parietal lobule (Dehaene, Piazza, Pinel, & Cohen, 2003).

The prefrontal contributions to mental arithmetic were not well described in the triple-code model, and it has been argued that elaboration is required in this and other areas (Arsalidou & Taylor, 2011). Results from a recent meta-analysis using activation likelihood estimation (ALE) have led to some suggested updates to the triple-code model, particularly in its description of the working memory processes (e.g., storage and procedures) that are involved in mental arithmetic. This meta-analysis considered experiments involving numerical tasks, grouped according to whether or not an arithmetic task was involved. Non-arithmetic numerical tasks included number and/or size comparison tasks, while arithmetic tasks included things like addition and/or subtraction. Both of these types of task were associated with activity in the parietal cortex, but the arithmetic tasks were also associated with prefrontal activity, in particular the middle and superior frontal gyri (Arsalidou & Taylor, 2011). This led to the proposal that prefrontal contributions to mental arithmetic were hierarchically organized, with the inferior, middle and superior frontal gyri making up the main subdivisions. Inferior frontal activity was associated with tasks with minimal storage and procedural requirements. Tasks with more moderate requirements, such as 2-digit addition problems, were associated with activity in the middle frontal gyri. High demand problems such as multi-step problems such as (14+19+21) were associated with activity in the medial and superior frontal gyri (Arsalidou & Taylor, 2011).

While results of this meta-analysis elaborated on the role of the prefrontal cortex, they directly challenged the triple-code model in terms of the role for the angular gyrus and the other parietal structures. The triple code model predicts that arithmetic fact retrieval would be associated with activity in the thalamus, basal ganglia and left angular gyrus, whereas the meta-analysis suggested that both right and left AG activity is associated with fact retrieval. In terms of calculation, the triple code model predicts that calculation requires the inferior (quantity manipulation) and superior (attention) parietal cortex, while Arsalidou & Taylor (2011) propose that a fronto-cingular network is crucial for calculation.

Clearly, there exists some difference in the neural systems implicated by these two models in mental arithmetic, which can be attributed to the different ways they were generated. The initial triple-code model was based on lesions studies (Dehaene & Cohen, 1997) and the IPS contributions were later updated using a meta-analysis of neuroimaging studies that focused on the role of the parietal cortex and did not consider other brain structures in detail (Dehaene et al., 2003). The recommended updates by Arsalidou and Taylor also employed a meta-analytic approach, but focused on a whole-brain approach to mapping out the brain regions associated with mathematics (Arsalidou & Taylor, 2011). One commonality, however, is that neither account was intended to provide commentary on the result of practice on these neural systems. In other words, the above discussed models take a static view of the brain regions underlying mental arithmetic. Much is known about how individual differences and training affect the neural correlates of arithmetic (Delazer et al., 2003; Grabner et al., 2007; Grabner, Ischebeck, et al., 2009; Ischebeck et al., 2006), but these studies are not yet integrated into models of mental arithmetic. For instance, a person who is well practiced at performing mental calculations might be able to do so without imposing the same cognitive demands as a person who rarely performs such calculations. Would these differences in performance be reflected in differential recruitment of the prefrontal cortex, as the meta-analysis might suggest, or the IPS, as is suggested by the triple-code model?

To answer questions such as these, the impacts of training on mental arithmetic can be examined. Skill acquisition is frequently accompanied by an anterior-posterior shift in activation, which has been interpreted to imply a shift from more domain-general prefrontal mechanisms to more task or domain-specific processes (Poldrack, 2000). In the case of mental arithmetic, this is commonly thought to reflect a shift from more working-memory intensive calculation-based strategies to stronger reliance on direct retrieval of specific arithmetic facts (Delazer et al., 2003; Imbo & Vandierendonck, 2008). However, it is unlikely that training effects are limited to a switch in strategy resulting from memorization. Practicing the retrieval of the solution to an arithmetic problem may decrease the time and resources required to retrieve said solution. Conversely, practicing a more complex calculation, such as a two-digit addition problem, might have beneficial effects in terms of behavioral performance, even in the case that the solution to the problem does not become memorized. This effect is particularly interesting because it is often neglected within the training literature, and may involve neural systems beyond those covered by the models described above.

1.2 Studies of arithmetic learning/training

The first fMRI study to investigate functional brain activation changes associated with learning arithmetic compared trained and untrained multiplication problems (Delazer et al., 2003). During training, participants repeatedly solved the same set of multiplication problems across several sessions over the course of a week. Following training, participants solved trained and novel, untrained problems as changes in brain activity were measured by means of fMRI. Greater activation was shown for trained versus untrained problems in the left angular gyrus (AG), inferior temporal gyrus, and anterior cingulate cortex. The reverse contrast (i.e., untrained > trained problems), revealed widespread frontoparietal activation. Since then, other training studies have consistently found either left or bilateral AG activity to be greater in the trained than the untrained condition (Delazer et al., 2003, 2005; Grabner, Ischebeck, et al., 2009; Ischebeck, Zamarian, Schocke, & Delazer, 2009) , with the other most consistent source of activity being in the anterior cingulate cortex (Delazer et al., 2003; Grabner, Ischebeck, et al., 2009; Ischebeck et al., 2009). Given that both of these regions are associated with a myriad of functions, the specificity of these training effects to arithmetic is of considerable interest. One of these studies did examine this by training a figural-spatial task along with an arithmetic task (Grabner, Ischebeck, et al., 2009). The difference between the arithmetic and spatial training effects was that the mid cingulate was more active in the trained arithmetic > untrained arithmetic contrast and the precuneus was more active in the figural-spatial trained > figural-spatial untrained contrast. AG activity was seen in the contrast of trained > untrained for both the arithmetic and figural-spatial task. Thus, the figural-spatial task and the arithmetic task had a common element which recruited the AG. One account of AG function proposes that the angular gyrus subserves the mapping between a symbol and its referent (Ansari, 2008). In this case, the arithmetic training results in a mapping between the symbols in the problem (2 x 4) and the solution (8). The figural-spatial task required participants to count the number of faces on a variety of 3D polygons, and so one way to become proficient on this task was to create a mapping between a 3D image and a number. However, given that the AG is associated with many other functions , it remains possible that the AG serves other roles within mental arithmetic beyond symbol-referent mapping.

One way to determine whether the arithmetic training effects seen in AG are related to something other than symbol-number mappings would be to look at problems where the strategies did not shift. Solving by fact retrieval is made possible by having a particular number (the solution) mapped to a particular symbol (the arithmetic problem), while this is not the case when problems are solved using a procedural problem solving strategy. Thus, any training effects produced in conditions where changes in performance could *not* be explained by a shift to fact retrieval (e.g., increased use of symbol-number mapping) could be informative in determining the specificity of AG effects. This type of analysis would require the tracking of pre- and post-training strategy in order to group problems according to how they were solved.

However, none of the training studies performed to date tracked pre- and post-training strategy, so that for any given trial it is unknown whether a shift in strategy had occurred. This is important since individual differences in strategy use are known to be present in the population, with individuals high in math competence tending to solve more problems through fact retrieval, and individuals low in math competence tending to solve more problems through effortful calculation (Geary, Hoard, Byrd-Craven, & DeSoto, 2004). Thus, in any study of arithmetic training, participants may be using different strategies at the outset of training, and may not be starting from an equivalent point. Indeed, individual differences in arithmetic knowledge and competence can make the interpretation of training data difficult.

1.3 Individual differences

Individual differences in math competency are known to correlate with activity in some of the brain regions identified by the training studies listed above. An early study examining this compared perfect performers (100% accuracy) against imperfect performers (92% average accuracy) on an addition and subtraction task (Menon et al., 2000). Region-of-interest (ROI) analyses were used to measure activity in three parietal regions. One of these regions, the left angular gyrus, showed a significant group effect, with activity being lower in perfect than in imperfect performers. Another study which examined the numerical basis of mathematical competence found the opposite pattern, with more competent performers exhibiting more activation in the left AG while solving single- and double-digit multiplication problems (Grabner et al., 2007).

At first glance these two sets of findings appear to be at odds with each other; however, a critical difference between the two studies was the threshold used to separate high and low performers. In fact, both the perfect and imperfect performers from the study by Menon et al. (2000) would have been categorized as mathematically competent in the Grabner et al. (2007) study – thus the comparisons made by each study are not equivalent. Thus, a preliminary conclusion from this data is that the AG is an important structure in arithmetic problem solving, but that within highly competent individuals, more efficient use (e.g., lower activation) of this structure is associated with better performance. In other words, the relationship between performance and AG activity is not necessarily linear.

Why, then, the difference between angular gyrus activity in high and low competence individuals? The triple-code model (Dehaene et al., 2003) suggests that AG activity is associated with arithmetic fact retrieval, and this is consistent with the training data discussed in the previous section as well as the notion that people with better arithmetic skills have more arithmetic solutions committed to memory (Geary et al., 2004). This association between fact retrieval and AG activity has been directly investigated by comparing problems solved by different strategy types. Specifically, in a recent study (Grabner, Ansari, et al., 2009), a group of adults were presented with arithmetic problems while undergoing an fMRI scan, after which they indicated what kind of strategy (memory or calculation) they used to solve the problems. Memory problems were the problems where a solution immediately came to mind without any intermediate steps, such as when someone is asked “what is the answer to 2 + 2” and “4” is reflexively retrieved from memory. If any other steps were required, such as counting, and/or the retrieval of intermediate solutions, then the problems were labeled as calculated. A contrast of memorized > calculated problems revealed focal activity in the left AG, with the reverse contrast revealing widespread fronto-parietal activity (Grabner, Ansari et al., 2009).

Before proceeding, two key concepts must be clarified. The first is the nature of the difference between solving by calculation and solving by memory. At first glance this differentiation may appear to be dichotomous. However, this is not the case, because the process of calculation invariably relies on the process of fact retrieval. Even when using a simple strategy such as counting, a person must have the series of numbers they are counting through (i.e., 5, 6, 7, 8) committed to memory. Thus it must be stressed that the distinction between a memorized and a calculated problem is that solving through memory is done without any awareness of intermediate operations being performed before the solution is produced, whereas calculated problems require one or more intermediate steps (which will include the retrieval of arithmetic-related facts) in order to arrive at the solution.

The second key concept that must be clarified also relates to the retrieval of a solution from memory. The AG is typically associated with ‘reflexive’ retrieval from memory (Cabeza et al., 2008), and it is this term ‘reflexive’ which requires some discussion. Though pervasive in the literature, it is imprecise from a mechanistic standpoint. In this thesis, the terms reflexive or automatic have specific meanings when applied to the retrieval of arithmetic facts from memory. Specifically, the process of retrieval is said to be reflexive when it is prompted simply by exposure to a stimulus (2 + 2). By contrast, a retrieval operation may be non-reflexive (or effortful) when an arithmetic stimulus is recognized as familiar, but the solution does not come to mind immediately.

Returning to the interpretation of the training studies presented in the previous section, the association between fact retrieval and AG activity (Grabner, Ansari, et al., 2009) seems quite reasonable. Greater AG activity for trained rather than untrained problems suggests that training resulted in more problems being committed to memory, however this assumes that all participants were employing a procedural calculation strategy at the study outset. This may not have been the case due to heterogeneity of strategy use between individuals (Campbell & Xue, 2001; LeFevre, Sadesky, & Bisanz, 1996). In other words, a problem solved by calculation in one person may be solved by fact retrieval in another. Thus, any training study which does not track strategy use is limited in its interpretability, because participants may not all be starting from the same point (e.g., some may already have problems committed to memory).

Developmental differences also play a role in modulating brain activity during mental arithmetic. One study compared brain activity in a group of participants from the ages of 9 to 18 by contrasting an arithmetic verification task (where the participant pressed a button when the correct answer appeared in a list of numbers) against a push-for-zero task (where the participant simply indicated whether zero was present in a list of numbers). The activation resulting from this contrast was then correlated with chronological age and it was found that parietal and temporal (e.g., AG and middle temporal) cortex activity positively correlated with age, whereas frontal and hippocampal activity correlated negatively with age (Rivera, Reiss, Eckert, & Menon, 2005). In other words, older children activated more parietal structures (consistent with the triple-code model), than did their younger peers (who activated more frontal structures). However, because this study also did not track strategy use, it is possible that some of these differences can be explained by the fact that young children may rely more on procedural calculation, whereas older children, like adults, may rely more of fact retrieval to solve a set of arithmetic problems.

Taken together, research into the neural underpinnings of mental arithmetic has clearly shown that training, strategy, and individual differences in competence and age modulate brain activity. However, it is unclear whether training effects can be explained as a shift in strategy (e.g., the cognitive processes are fundamentally different), or whether activity in structures like AG, IPS, SPL and the hippocampus may be modulated even in the absence of a shift in strategy (e.g., a refining of the activation patterns observed for the same cognitive process). In order to clarify these issues, both strategy and training effects would need to be measured within the same experimental paradigm, and individual differences in strategy use would also need to be controlled for.

1.4 Current project

Controlling for individual strategy use in the context of a training study represents a crucial step for advancing the understanding of the neural basis of calculation. Such a research strategy would allow for the observation of how differences in functional brain activation arise as a function of strategy, learning, and individual ability level within the same study. To perform such an investigation, a novel paradigm called Customized Arithmetic Training (CAT) was developed for the purposes of the current thesis. The CAT paradigm generates individually tailored problem sets based on self-reported strategy, such that each participant begins the training using the same mixture of strategies (half calculated, half memorized). In other words, the problems solved will differ between participants but the balance of procedural and retrieval problems will be equated between participants. In this way the CAT approach controls for individual differences in strategy use in a way that was not afforded by any of the previous studies on the neural correlates of mental arithmetic. After these problem sets are generated, each set is divided, with a subset of these problems being assigned to training. Following a 6-day training period, the participants return to the lab for an fMRI scanning session, where participants solve each of the problems obtained on the first visit (e.g., both trained and untrained) twice. Following this, they provide a final strategy report for each problem using a paper and pencil test (outside the scanner). In this way, pre- and post-training strategy measures are obtained for each problem, allowing for the separation of calculation problems that became memorized due to training from those that did not. Furthermore, training effects on memorized problems, which have been largely ignored in the literature, can also be investigated, as the CAT paradigm allows for the identification of problems that were memorized pre and post training.

This design addresses several outstanding issues in the study of mental arithmetic. The first concerns the reliability and face validity of self-reported strategy, as well as whether it is possible to develop a computerized system which can balance strategy across participants (Chapter 2). Secondly, it allows for a more detailed examination of the neural correlates of fact retrieval by isolating problems which were memorized through training and comparing them against other problems, such as memorized problems that were identified by CAT as problems solved by retrieval prior to training (Chapter 3). Finally, by isolating memorized and calculated problems whose strategies did not shift through training, it can identify training-induced shifts in activation that specifically reflect optimizations of fact retrieval or procedural calculation (Chapter 4).

1.5 Chapter 2 outline

Chapter 2 describes the development the CAT paradigm. Because of the novelty of this approach, two behavioral experiments were conducted to assess the feasibility of the CAT protocol and then to ensure that the self-reported strategies collected were reliable and valid. In the first experiment, issues of reliability and face validity were explored by comparing strategy reports on two tasks, a voice production task where the participant spoke the solution aloud, and a choice task where the participant chose the appropriate solution from a two-item list of potential solutions. In this experiment the voice task was used (in addition to the choice task) to obtain the problem sets because it offered a more fine grained measure of reaction time, which was necessary to provide commentary on the face validity of the self-reports (memorized problems were expected to be solved more quickly, whereas calculated problems were expected to be solved more slowly). Having established the reliability and validity of these self-reports, a second experiment was conducted, where the choice task (which was better suited for fMRI research because it required minimal movement from the participant) was used to obtain the problem sets. In both of these experiments, the participants also underwent a 5-day training program using a subset (half memorized, half calculated) of these problems. Participants then returned to the lab for a post-training visit and performed the same tasks as they did pre-training, solving all the problems in both the untrained and trained problem sets. Strategy, reaction time, and accuracy were again collected, which provided information about learning rates and behavioral improvements induced by training.

1.6 Chapter 3 outline

Having successfully developed the CAT paradigm in Chapter 2, Chapter 3 describes its use in the context of an fMRI experiment with a group of adult participants. Because of the large volume of data collected in this experiment, the analyses were split between

Chapters 3 and 4. Chapter 3 focuses on the switch from effortful calculation to fact retrieval, which is known to be an important component of making arithmetic easier to perform by decreasing working memory demands (Imbo & Vandierendonck, 2008), and is also the most common explanation for training effects in previous studies of arithmetic training (Delazer et al., 2003). These recently memorized problems (i.e., problems that were previously calculated but became memorized as a result of training) are compared to calculated problems as well as to problems that were memorized before the study began (i.e., remote memories). Due to the novelty of the CAT paradigm, the first contrast presented in this Chapter is a comparison of untrained calculated and memorized problems, to determine whether the results are consistent with previous research into arithmetic strategy (Grabner, Ansari, et al., 2009). Recently memorized facts are then compared with three other problems types; untrained calculated problems, untrained memorized problems, and trained memorized problems. Comparing recent memories to untrained calculated problems is very similar to the contrasts that are featured in most training studies (e.g., Delazer et al., 2003), and will confirm whether training effects previously reported reflect a shift in strategy. Finally, comparing recently memorized problems against both trained and untrained memorized problems (two novel contrasts afforded by this design), will determine whether there exists a temporal gradient between brain activity associated with older and newer arithmetic facts, as is frequently the case with semantic memories (Smith & Squire, 2009) .

1.7 Chapter 4 outline

After examining the neural correlates of fact retrieval in Chapter 3, the optimization of both fact retrieval and procedural calculation will be examined in Chapter 4. To do this, both the main effects and interactions between strategy and training will be identified. Thus, only the problems which *did not* exhibit a change in strategy will be analyzed, allowing for the isolation of training effects on a given strategy (Poldrack, 2000). In other words, comparing trained to untrained memory problems should expose regions critical for efficient performance of arithmetic fact retrieval, and training calculated problems should expose regions critical for effortful calculation in the absence of a strategy shift.

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Chapter 2

2 The development of the Customized Arithmetic Training program

2.1 Introduction

One of the main challenges of studying mental arithmetic is inter-individual variability in strategy use - one person may solve a given problem by retrieving its solution from memory, whereas another may need to solve the same problem through effortful procedural calculation. To date, studies of mental arithmetic have largely relied on fixed problem sets. Despite the advantage of ease of implementation, use of fixed problem sets also carries critical disadvantages due to heterogeneity of strategy use present in the population. In other words, the use of a fixed problem fails to address wide individual differences in the way in which the problems are solved with no way of capturing this between-subject variability. This is of particular concern in studies of arithmetic learning, where training effects such as shifts from effortful calculation to retrieval from memory are of critical importance. Therefore if different participants solve the problems with different strategies at the outset of the training, the effects of training will differ between participants with some undergoing shifts in strategy while others may experience a training effect on an already memorized problem. This Chapter details the development of a novel arithmetic training program, known as Customized Arithmetic Training (CAT), which balances strategy use between individuals in a given sample in the context of an arithmetic training program. By doing so the training program can equate participants on strategies in order to more adequately compare participants with one another and to understand the effects of training on different strategies Ultimately, this training program will be put to use in an fMRI investigation of the neural correlates of arithmetic learning (see Chapters 3 and 4).

2.1.1 Strategies for solving arithmetic problems

Arithmetic strategies can be broadly divided into two categories – fact retrieval and effortful procedural calculation. Adult participants rely primarily on recall from memory to answer simple problems (Geary, Hoard, Byrd-Craven, & DeSoto, 2004), but for more complex problems (e.g., addition problems with large sums, such as 35 + 26,), other procedural strategies come into play, such as counting, transformation (e.g., adjusting the problem operands such that the solution can be retrieved from memory and then working from there), or the use of rules or heuristics (LeFevre, Sadesky, & Bisanz, 1996). Distinguishing between these problem types is important because they make use of different cognitive processes - solving through recall relies solely on reflexive retrieval from memory while procedural solving involves retrieval as well other cognitive processes such as working memory, strategy selection and planning (Imbo & Vandierendonck, 2008).

2.1.2 Assessing strategy

The most viable way to measure problem-solving strategy is to use self-report measures, which are obtained by asking the participants themselves to describe the strategy they use to solve a given arithmetic problem. One of the first studies to use this method to glean insight in the mechanisms underlying arithmetic processing used trial-by-trial self-reports to assess arithmetic strategy use in adults (LeFevre et al., 1996). It was found that a retrieval strategy was used on 71.2% of trials, while procedural calculation was performed the remainder of the time. Since then, self-reported strategy has become a widely-used indicator of mental arithmetic processes, with some caveats. Most critically, task instructions can bias both self-reported strategy and response latencies (Kirk & Ashcraft, 2001). For instance, when instructions suggest that either procedural or retrieval strategies are the most common types of strategies to use, people biased towards retrieval report more retrieval strategies but also produce solutions more quickly, whereas the opposite pattern emerges for those biased towards procedural strategies. Thus, task instructions must not be suggestive that a particular strategy should be used by the participant. Provided that this is the case, however, self-reported strategy is a very useful measure in the study of mental arithmetic.

2.1.3 Heterogeneity of strategy use

To date, research on arithmetic learning has predominantly employed the same problem sets for every participant (Delazer et al., 2003; Grabner et al., 2009; Ischebeck et al., 2006), which imposes limitations due to heterogeneity in strategy use. One way this has been demonstrated was by comparing university students with different educational backgrounds and levels of arithmetic proficiency, specifically, students from China who had been educated in either China or Canada as well as non-Chinese Canadian students who were educated in Canada (J. I. D. Campbell & Xue, 2001). Two math tests were performed; one with simple arithmetic using all operations (e.g., 3 + 4, 7 - 3, 3 X 4, 12 / 3), and one with more complex, multi-step addition, multiplication and subtraction problems, and division problems. The complex arithmetic test was done in pencil and paper format, and it was found that Chinese students outperformed the non-Chinese Canadian students in terms of accuracy. For the simple arithmetic tests, problems were solved one at a time on using a computer based test, and participants reported their strategy after solving each problem. Chinese students who obtained their education in either China or North America relied more on retrieval strategies (87% and 85%) than did Canadian students (72%), and also outperformed North American students in terms of reaction time and accuracy. This highlights the heterogeneity of strategy use that can be present in any given population, which inevitably complicates the interpretation of results from studies of arithmetic learning if fixed problem sets are employed, because people are not necessarily starting using the same mixture of strategies when they begin the training program.

2.1.4 Training and strategy

Training effects on mental arithmetic have been assumed to reflect a shift from more working-memory intensive calculation-based strategies to stronger reliance on direct retrieval of specific arithmetic facts. Nevertheless, this view remains largely untested because the strategy used to solve each problem has never been measured in these training studies. For instance, problems in the trained set are likely to be composed of two main types – newly formed memories of arithmetic facts and well-rehearsed procedural calculations, which would draw preferentially on aspects of the declarative and procedural memory systems, respectively. If strategy could be tracked in the context of a training study, then training effects could be described in better detail, because newly memorized problems could be separated from the well-rehearsed calculations. This is an important methodological improvement, because it will allow for more careful study of arithmetic training effects. Furthermore, it would enable the assessment of individual differences in learning rates (e.g., the amount of problems a participant may memorize through training), something which has not been widely discussed in the training literature.

2.1.5 Current study

The ultimate goal of the current study was to develop a novel paradigm that was suitable for use in an fMRI study of training effects on mental arithmetic. This paradigm, known as Customized Arithmetic Training (CAT), used individually tailored problem sets that were calibrated such that each participant, at the outset of training, solved an equal number of arithmetic problems by fact retrieval, and an equal amount of arithmetic problems through procedural calculation. In this way, strategy use was tracked pre- and post-training, and the balance of strategies would be equal between participants. Because of the novelty of this paradigm, two experiments were conducted with the aim of assessing five critical issues present in this type of research.

The first aim was to assess the face validity of self-reported strategy use by using a voice production task where the participant spoke the solution aloud, allowing for a precise estimate of reaction time. The second aim was to determine whether the strategy reports were reliable both within and between task – that is, whether participants would consistently report using the same strategy for a given problem, even if the response format differed. The third aim was to determine whether a task suitable for fMRI could be used to create the CAT sets. The fourth aim was to assess individual differences in strategy use as well as individual differences in learning rates resulting from the training problem. Finally, the fifth aim was to evaluate the effectiveness of the problem finding algorithm that was used to generate the CAT sets.

In the first experiment, issues of reliability and face validity were explored by comparing strategy reports on two tasks; a voice production task where the participant spoke the solution aloud, and a choice task where the participant chose the appropriate solution from a 2-item list of potential solutions (Aims 1 and 2). In this experiment a voice task was used to obtain the problem sets because it offered a more fine grained measure of reaction time, which was necessary to provide commentary on the face validity of the self-reports (memorized problems were expected to be solved more quickly, whereas calculated problems were expected to be solved more slowly). Having established the reliability and validity of the self-reports, a second experiment was conducted, where the choice task (which was better suited for fMRI research because it required minimal movement from the participant) was used to obtain the problem sets (Aim 3). In both of these experiments, the participants also underwent a 5 day training program using a subset (half memorized, half calculated) of these problems. A post-training visit to the lab provided an indication of the stability of the self-reports over time, as well as information regarding the expected rates of memorization among the trained calculated problems (Aim 4).

2.2 Methods – Experiment 1

2.2.1 Objective

Experiment 1 examined the within and between task reliabilities of the self-reported strategies using a voice production task (where the participant speaks the solution to the problem aloud) and a choice task (where the participant selects the correct solution from a list using a button press), as well as the training effects on problems of each strategy type. In Experiment 1, training sets were generated using participants' self-reported strategy using a voice production task. A voice task provides good timing information due to the use of a voice-activated switch, which records the reaction time of each utterance. Each problem was shown twice which allowed for the assessment of within task reliability (reliable problems being identified as problems which were solved by the same strategy for both exposures). The between task reliability of self-reported strategy was then examined using an arithmetic choice task (where participants were required to select the correct response from two possibilities using a button press). Strategy reports were deemed reliable if they were solved by the same strategy on the voice and choice task.

Following this, training effects were examined. Problems from the CAT sets were assigned to either the trained or untrained (control) condition. Participants performed the training (described in Methods) for 5 days and then returned to the lab for a follow-up test, using the voice production task. This allowed for the identification of problems which shifted from procedural calculation to retrieval as a result of training, as well as changes in reaction time and accuracy. It also allowed for the assessment of the reliability of the strategy reports over time by examining the strategy reports of the untrained problems before and after the training period (problems in the untrained set were not expected to be solved by a different strategy post-training).

2.2.2 Participants

Participants included 18 undergraduate and graduate students (10 males, 8 females, Mean age 22.33 yrs, StdDev, 2.40 yrs) enrolled at The University of Western Ontario, Canada. Participants were recruited through posters distributed on campus. All participants completed all experimental conditions and provided informed consent using documentation that was approved by the Psychology Research Ethics Board at the University of Western Ontario.

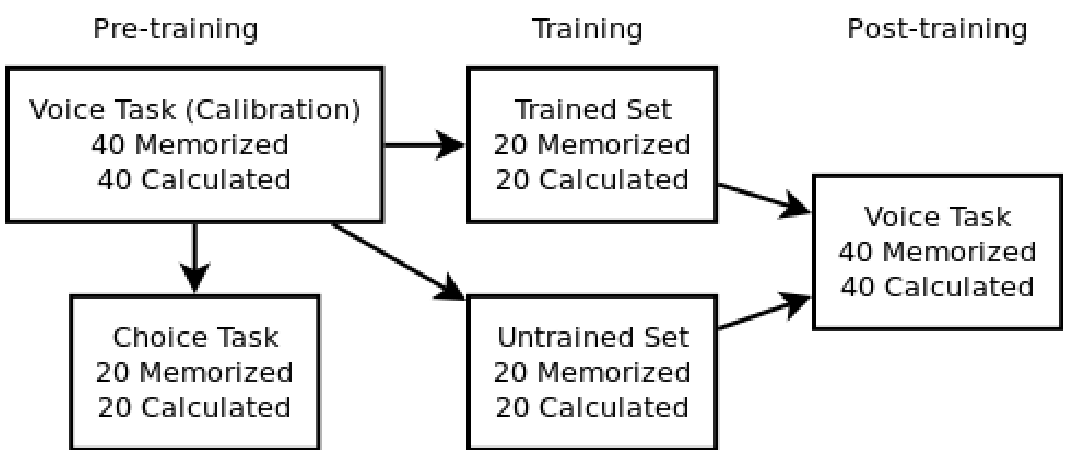

Figure 2.1: Flowchart of Experiment 1 procedure

2.2.3 Procedure

2.2.3.1 Pre-training – Voice production task

The goal of this stage was to obtain a set of 80 arithmetic problems, 40 of which were solved by memory and 40 of which were solved through calculation. During pre-training participants solved a series of arithmetic problems (3 + 4 = ?). For each problem, participants spoke the solution out loud. Reaction times were measured by means of a voice-activated switch. Participants were then prompted to indicate whether they retrieved the solution from memory or performed a more effortful calculation (procedural problem solving strategy), again through voice response. The experimenter then inputted the strategy and the accuracy into the program using a key press. To assess the reliability of self-reported strategy, individual problems were presented twice over the course of pre-training. Only reliable problems, that is, problems which were responded to twice with the same strategy, were retained. For both Experiments 1 and 2, 40 memorized (MEM) and 40 calculated (CALC) problems were obtained.

2.2.3.2 Calibration

The calibration algorithm used to identify problems worked as follows. Initially, the program searched for problems solved by procedural calculation. It accomplished this by gradually increasing the size of the operands (starting from single digit problems, e.g., 2 + 3), until the participant began to respond that they were using the CALC strategy. The operands continued to increase until 10 CALC problems were collected. Once this point was reached, the program would also start to present some of the previously shown problems again to assess the reliability of the self-reports. Problems that were solved by the same strategy both times were included in the training sets, and the others discarded.

Once the first 10 CALC problems were obtained, the program would search for either more CALC problems or more MEM problems, depending on which were in shorter supply in the program's database. If MEM problems were being sought out, the size of the operands was decreased from one problem to the next. If CALC problems were being sought out, the size of the operands was increased. This was done because it was expected that individuals would reach a point at which they could no longer retrieve solutions from memory and would thus have to switch a procedural calculation based strategy (though the point at which this switch occurred was expected to vary from person to person due to individual differences). During the search process, the shift in operand size was more pronounced if one strategy was being sought out, but the previous trial's strategy had been the other strategy. That is, if the previous trial had been solved by the MEM strategy, and CALC was being sought out, the size of each operand was increased by 5 or 6. However, if a CALC strategy had been previously used, then the operands would only be increased by 1, 2 or 3. If an error was made, the problem was eliminated from inclusion in the training set and the size of the operands was also reduced. Ultimately, 40 reliable MEM and 40 reliable CALC problems were collected.

2.2.3.3 Pre-training – Choice task

After the 40 MEM and 40 CALC problems were collected, the voice production task concluded and the choice task was administered using the problems that were just obtained. Participants were presented with an arithmetic problem for 1 second followed by a blank screen for 2 seconds. After the pause, they were presented with two numbers: the solution and a distractor (which appeared below the problem). The participant indicated with keyboard response which side of the screen the correct answer appeared on. The side of the screen on which the correct response appeared varied from trial to trial.

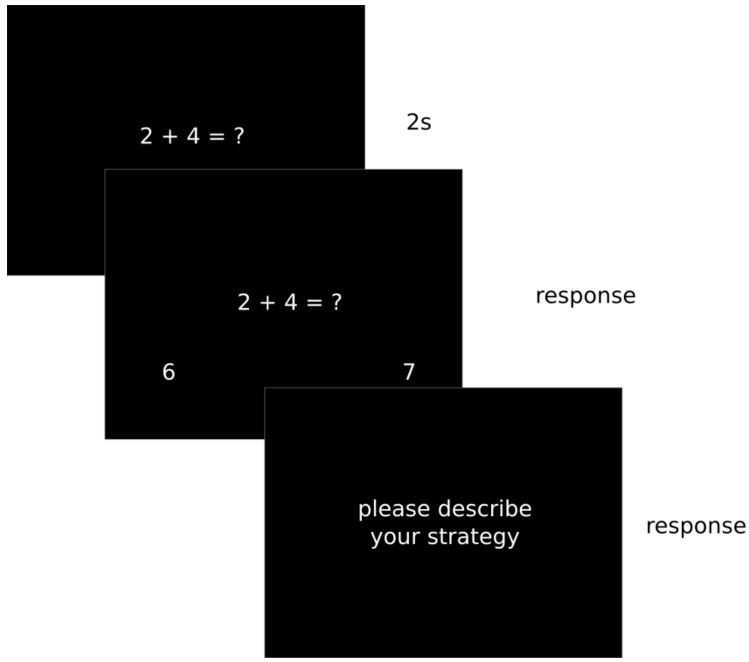

Figure 2.2: Sample trial of choice task. Participants were presented with a problem for 2s and then asked to select the correct answer from a 2-item list.

In the construction of a choice task, it is crucial to be mindful of the distractors used, to avoid the use of shortcut strategies not involving computation of the solution (e.g., participants make an educated guess based on the plausibility of the distractors). When shortcuts can be used, the retrieval processes involved may be different (Campbell & Tarling, 1996), as evidenced by the fact that error priming has different effects in verification (determining whether a presented problem/solution pairing was correct, e.g., 2+4 = 7?), versus production (saying the answer to a presented problem, 2 + 4 = ?) tasks. To discourage the use of shortcut strategies, the distractor lists had to be carefully constructed.

Each problem had a distractor list assigned to it from which potential distractors were drawn. The distractor list was determined based on parity and sum in order to provide distractors that are similar enough to the actual solution that guessing does not take place. When the parity of both operands was matched, a distractor of +-2 was part of the list. When the parity was mixed, a distractor of +-2 was part of the list. This was done because participants can use parity information to determine the parity of the solution, without actually solving the problem itself. When the sum was greater than 30, a distractor of +- 10 was part of the list. This was carried out so that participants could not determine the solution by examining only the first digit in any of the 2-digit problems. For each problem, all plausible distractors were randomly selected, such that participants would not come to expect a certain type of distractor based on the size and parity of the operands. For instance, for the problem “34 + 36”, potential distractors would include +-2 and +-10. Thus, for any given presentation of “34 + 36”, the participant might see 68, 72, 60, or 80 as the distractor.

As in the voice production task, after solving each problem, participants indicated the strategy they used to solve the problem through voice response. The strategy was then inputted into the program by the experimenter using a button press. Measures collected were accuracy, reaction time, and strategy. Due to concerns over participant fatigue, a random selection of half the MEM and CALC problems obtained during from the calibration stage were used in this stage of the experiment.

2.2.3.4 Training – Keyboard production task

20 CALC problems and 20 MEM problems were randomly assigned to training, with the remaining problems making up the untrained set. Training took place at the participant's home using their personal computer. Participants visited a website which guided them through the training process. Each day, for 5 days, participants solved 10 repetitions (in random order) of their 40 training problems (20 CALC and 20 MEM). The problem was presented onscreen in 18 point font and the participant had to type the solution and press ENTER when done (seen in Figure 2.3). Participants were given feedback when an error was made and had to solve the problem again. Participants solved 400 problems per day (200 MEM and 200 CALC), plus any problems which were repeated due to errors. Each trial from the participant's training was recorded on the web server. Compliance was assured by checking that participants completed their 400 trials each day.

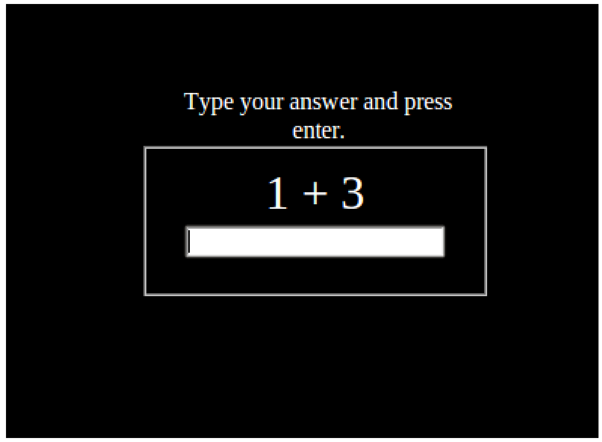

Figure 2.3: Screenshot of the training website. Participants were shown an arithmetic problem and typed the solution in the box.

2.2.3.5 Post-training – Voice production

The post-training lab visit used the voice production task. Participants were presented with the 40 problems that made up their training set, as well as 40 untrained problems (20 CALC and 20 CALC) that were previously set aside. As during pre-training, each problem was shown to the participant twice, and a strategy report was obtained for each. This allowed for the measurement training effects – namely, any shifts in strategy and improvements in performance (RT and ACC). The order of problems was pseudo-randomized such that the same problem did not appear twice in a row.

2.3 Results - Experiment 1

2.3.1 Pre-training – Voice production task

2.3.1.1 Frequency of self-reports

Table 2.1 shows the frequency of each strategy type obtained through self-report. As mentioned, each problem was shown twice to the participant, and each time they were prompted to indicate the strategy they used to solve the problem. Therefore, four strategy types were possible – calc (where the participant used a calculation strategy both times), mem (where the participant used a memory strategy both times), cm (where the participant used the calculation strategy first, then the memory strategy a second time), and mc (where the participant used the memory strategy first and then the calculation strategy). The majority of the problems presented were consistently solved with the memory or the calculation strategy.

strategy report	mean	SD	min	max
calc	49.3%	3.0%	44.9%	55.1%
calc->mem	4.6%	2.2%	0%	10.0%
mem	42.8%	2.9%	36.2%	47.4%
mem->calc	3.4%	2.4%	0%	9.6%

Table 2.1: Frequencies of strategy report in the Experiment 1 Voice Task. Each cell represents the portion of the total problems shown to the participant.

2.3.1.2 Individual differences

Figure 2.4 shows the results of the calibration session for Experiment 1, done using the voice production task. While it was the case in participants that calculated problems took longer to solve than memorized problems (as well as having larger sums), the ranges of sums and reaction times for a given strategy varied between participants. Specifically, memorized problems varied in average sum from 11 to 40, while calculated problems varied in average sum from 30 to 77. In terms of mean reaction time, calculated problems varied from 1.26s to 3.85s, while memorized problems ranged from .84s to 1.7s in mean reaction time. Thus, there was no clear dividing line between memorized and calculated problems that would apply to all participants, either on the grounds of absolute reaction time or absolute sum. These data therefore clearly speak against the utility of using fixed problem sets in studies of mental arithmetic and demonstrate the power of designing problem sets that are customized according to the individuals' strategies. Furthermore, they indicate that problem size should not be used as a proxy for strategy, unless it is considered in the context of a single participant’s data.

There were also individual differences in the time it took to find 40 memorized and 40 calculated problems during the calibration session. The shortest session was approximately 17 minutes (183 trials), and the longest session was approximately 30 minutes (222 trials).

2.3.1.3 Strategy effects (Pre-training)

To examine the effect of self-reported strategy, a paired t-test was performed to determine whether a difference existed between RTs for memorized (mem) and calculated (calc) problems. There was a significant difference in the response times between mem (M=1.10, SD=0.23) and calc (M=2.32, SD=0.62) problems; $t(17.0)$=10.91, p<0.001, d=2.57. To examine the relationship between accuracy and strategy, a paired t-test was performed and there was no significant difference between the scores for mem(M=99.92, SD=0.32) and calc(M=99.64, SD=0.59) problems; $t(17.0)$=-1.66, n.s.

It was also of interest to determine the relationship, if any, between strategy and sum. A paired t-test revealed a significant difference in the sums for mem(M=24.29, SD=9.12) and calc(M=47.81, SD=14.17) problems; $t(17.0)$=11, p<0.001, d=2.58. Consistent with previous research, memorized problems had smaller sums than calculated problems.

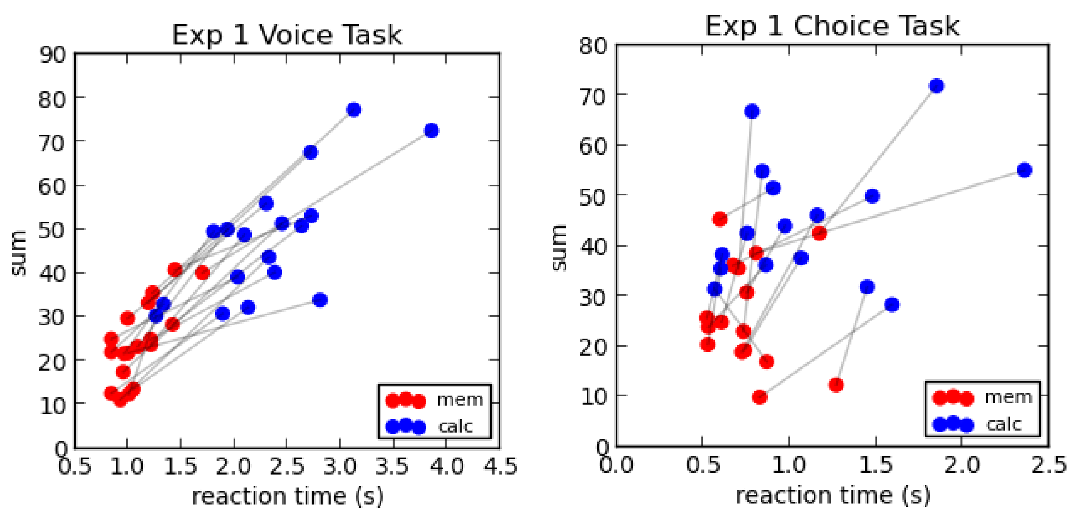

Figure 2.4: Relationship between pre-training reaction time and sum (i.e., the sum of the operands) for memorized and calculated problems, for the voice and choice tasks (Experiment 1).

2.3.2 Pre-training – Choice task

2.3.2.1 Frequency of self-reports

Table 2.2 shows the frequencies of the self-reported strategies obtained after the choice task was administered. As a reminder, a subset of the problems obtained in the calibration phase were presented again using the choice task. Values from this table indicate the proportion of problems obtained during calibration (voice task) that were solved by the same strategy using the choice task. While reports were fairly consistent for both categories, memorized problems were more consistent than calculated problems. A potential reason for this could be that calculated problems were being committed to memory after repeated exposures.

strategy	mean	SD	min	max
calc	79.1%	18.3%	23.5%	100%
mem	84.7%	15.7%	50%	100%

Table 2.2: Consistency of self-reported strategies after the choice task

2.3.2.2 Strategy effects

Strategy effects on the choice task were also examined. Due to computer error data was lost for 2 participants (thus for this analysis N=16). A paired t-test revealed a significant difference between the scores for mem (M=0.75, SD=0.21) and calc (M=1.11, SD=0.50); $t(15.0)=3.40$, $p=0.004$, $d=0.85$. Note that these RTs appear faster than those from the production task, because in the choice task participants were responding to the distractors after having seen problem for 2s. Given the low RT for memory problems obtained during the voice production task (M=1.10, SD=0.23), most participants had the solution to the memorized problems in mind before the distractors were even presented, explaining the very short reaction time. In terms of accuracy, the means of mem (M=98.55%, SD=2.28) and calc (M=96.77%, SD=8.31) did not differ, with a paired t-test showing no significant difference; $t(15.0)=-0.85$, n.s.

2.3.3 Post-training – Voice production task

2.3.3.1 Frequency of self-reported strategies

Upon post testing, three main problem-solving strategies were present – calculated (calc-calc), remote memory (mem-mem), or recent memory (calc-mem). Calculated problems were solved both pre and post by procedural calculation, remote memory problems were solved both pre- and post-training by fact retrieval, and recent memory problems were solved pre-training by calculation, and post-training by fact retrieval. Problems were further labeled by whether they were part of the training set or not. Table 2.3 shows the frequencies of the strategy reports, broken down by training and initial strategy. As would be expected, a greater proportion of recent memory problems appeared in the trained group than in the untrained group.

	Initially memorized		**Initially calculated**	
Training	remote mem	mem->calc	calc	recent mem
Untrained	*M*=95.4%, min=71.4%, max=100%	*M*=4.6%, min=0%, max=28.6%	*M*=79.7%, min=27.3%, max=100%	*M*=20.3%, min=0.00%, max=72.7%
Trained	*M*=99.5%, min=90%, max=100%	*M*=1.6%, min=0%, max=16.7%	*M*=25.6%, min=0%, max=81.3%	*M*=74.4%, min=18.8%, max=100%

Table 2.3: Frequencies of various strategies used by participants. Cells show means and ranges for each pre-post strategy, organized by training and initial strategy.

2.3.3.2 Strategy effects (Post-training)

To examine the effects of strategy (on both trained and untrained problems), the initial strategy reports from the calibration session were used, because some conditions (such as untrained recent mem) did not occur in all participants. A main effect of strategy was found on both reaction time and accuracy. A paired t-test revealed a significant difference between the reaction times for remote memory (*M*=0.98, *SD*=0.14) and calculated (*M*=2.11, SD=0.58) problems; $t(17.0)=9.25$, $p<0.001$, $d=2.18$. There was also a significant difference between the accuracies for calculated (*M*=97.14, *SD*=3.52) and remote memory (*M*=99.89, *SD*=0.47) problems; *t*(17.0)=-3.19, *p*=0.005, *d*=0.75. Thus, the problems that were memorized pre-training were still solved more quickly and accurately than were calculated problems, even post-training. This can be seen in Figure 2.5, which further subdivides the calculated problems into the categories of calc and recent mem. Initial strategy was used in the analysis of main effects rather than the strategy conversion because some conditions (such as untrained recent mem) did not occur in all participants. RTs and ACCs for the various strategy subtypes are shown Figure 2.5, which provide a description of the qualitative differences between them.

2.3.3.3 Training effects

Training effects were also evident. There was a significant difference between the reaction times for untrained (*M*=1.54, SD=0.37) and trained (*M*=1.05, SD=0.14) problems; *t*(17.0)=7.27, *p*<0.001, *d*=1.71, as well as a significant difference between the accuracies for untrained (*M*=97.31, SD=2.81) and trained problems (*M*=99.58, SD=1.29); t(17.0)=-3.56, *p*=0.002, *d*=0.84. 2x2 ANOVA was conducted to test whether there was any interaction between strategy and training (examining only problems where a shift in strategy did not occur). For reaction time, a significant relationship was found, with $F(1, 17) = 22.32$, $p<0.001$. For accuracy, a significant relationship was also found, with $F(1, 17) = 8.09$, $p=0.011$. In both cases, the strategy effect was diminished in the trained condition, thus driving the interaction between strategy and training.

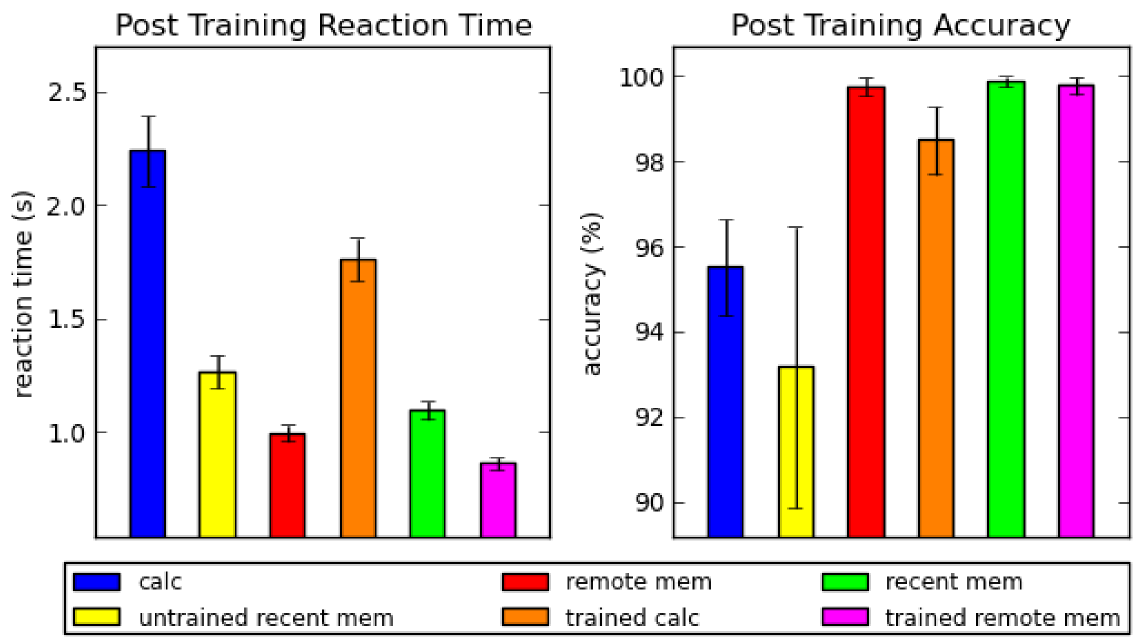

Figure 2.5: Post production reaction times and accuracies for various problems (Experiment 1, Voice Task)

2.4 Methods - Experiment 2

2.4.1 Objective

Experiment 1 assessed the utility of the CAT system using a task that involved the production of the solution to each problem by the participant. However the voice production task used to calibrate the CAT sets was known to be suboptimal for experiments involving neuroimaging. Voice response, while providing a better indication of reaction time, can contaminate fMRI data. Specifically, in fMRI experiments, motion artifacts induced by the movement of the jaw during speech can seriously degrade the quality of the collected data. Given that the ultimate goal of the CAT paradigm was that it be used in an fMRI investigation, the choice task, which required no movement of the head, and only minimal movement of the fingers, was the optimal task. In Experiment 1 it was established that the reliability of the strategy reports between the voice and choice task was high, thus in Experiment 2 the CAT sets were constructed using the choice task rather than the voice task. These CAT sets were then used in the same training system as

Experiment 1. As in Experiment 1, shifts in strategy and behavioral improvements were examined post-training.

2.4.2 Participants

Participants included 15 undergraduate and graduate students (8 males, 7 females, Mean age 21.60 yrs, StdDev, 2.47 yrs) enrolled at The University of Western Ontario, Canada. Participants were recruited through posters distributed on campus. All participants completed all experimental conditions and provided informed consent using documentation that was approved by the Psychology Research Ethics Board at the University of Western Ontario.

2.4.3 Procedure

2.4.3.1 Pre-training – Choice task

Experiment 2 followed the same logic as Experiment 1, but only the choice task was used during pre-training, thus the calibration of the problem sets was done using this task. The same number of problems was collected (40 MEM and 40 CALC). As in Experiment 1, each problem was shown to each participant twice to determine the consistency of the self-reports. Figure 2.2 shows a calibration trial using the choice task.

2.4.3.2 Training – Keyboard production task

The training in Experiment 2 was identical to Experiment 1 – 20 MEM and 20 CALC problems were rehearsed 10 times a day for 5 days, with participants accessing the training site on their home computer.

2.4.3.3 Post-training

The post-training lab visit used the same choice task as in the pre-training visit. Participants were presented with the 40 problems that made up their training set, as well as 40 untrained problems (20 CALC and 20 CALC). Each problem was shown to the participant twice, and a strategy report was obtained for each problem. This allowed the measurement of training effects – namely, any shifts in strategy and improvements in performance (RT and ACC). The order of problems was pseudo-randomized such that the same problem did not appear twice in a row.

2.5 Results - Experiment 2

2.5.1 Pre-training choice task

2.5.1.1 Frequency of self-reports

In Experiment 2, only the choice task was used, thus 2 self-reports were obtained for each problem. Table 2.4 shows the frequency information for these strategies. As in Experiment 1, consistently calculated and memorized problems were the most common types observed.

strategy	mean	SD	min	max
calc	49.8%	0.5%	48.7%	50.6%
calc->mem	1.1%	1.4%	0.0%	3.8%
mem	48.5%	2.0%	43.8%	51.3%
mem->calc	0.6%	0.9%	0.0%	2.5%

Table 2.4: Frequency of self reports for Experiment 2 pre-training (Choice Task)

2.5.1.2 Individual differences

Figure 2.6 shows the average sum and reaction time for each participant. Again, there were between-subject differences in terms of both reaction time and sum for memorized and calculated problems. Between participants, calculated problems had sums between 32 and 66, while memorized problems had sums between 12 and 50. Calculated RTs varied from 0.64s to 2.86s, and memorized RTs varied from 0.59s to 1.08s. Consistent with the results of Experiment 1, there was no clear dividing line between memorized and calculated problems in terms of absolute reaction time or absolute sum.

There was less of an RT difference between both problem types as compared to Experiment 1– this is because of the nature of the choice task, which gives the participants 2 seconds of solving time before prompting them for a response.

There were also individual differences in the duration of the calibration session. The session with the least trials (208 trials) took 26 minutes to complete and the session with the most trials (331) trials took 38 minutes to complete. These values were higher than in Experiment 1 for two reasons – first, the choice task took longer before the participant could respond and second, changes to the search algorithm were made. Specifically, more trials were placed in between the initial and repeated exposures of each problem. This change lowered the odds that the participant would remember seeing the problem during the session, but it increased the number of trials needed to complete the session.

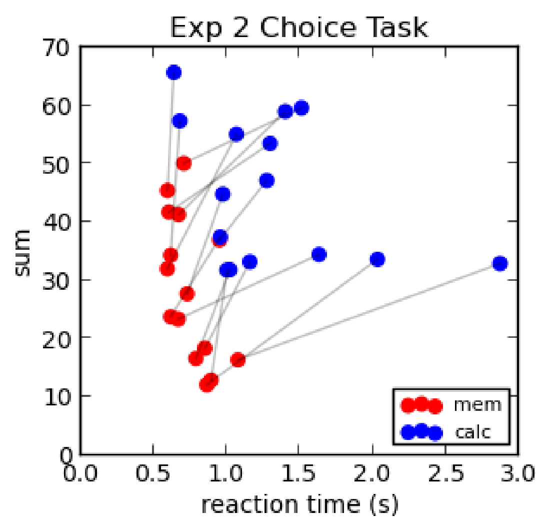

Figure 2.6: Relationship between reaction time and sum for Experiment 2 pre training (Choice Task)

2.5.1.3 Strategy effects

A paired t-test revealed a significant difference between the reaction times for memorized (M=0.75, SD=0.15) and calculated (M=1.30, SD=0.56) problems; $t(14.0)=4.44$, $p<0.001$, d=1.15. There was also a difference between accuracies, with a paired t-test revealing a significant difference between the accuracies for mem (M=0.98, SD=0.01) and calc (M=0.96, SD=0.03); $t(14.0)=-3.59$, p=0.003.

With regards to sum, a paired t-test was performed. There was a significant difference between the sums for memorized (M=28.84, SD=12.44) and calculated (M=45.16, SD=12.27) problems; $t(14.0)=14.00$, $p<0.001$, d=3.61.

2.5.2 Post-training – Choice task

2.5.2.1 Frequency of self-reports

Upon post testing, three main problem-solving strategies were present – calculated (calc-calc), remote memory (mem-mem), or recent memory (calc-mem). Calculated problems were solved both pre- and post-training by procedural calculation, remote memory problems were solved both pre- and post-training by fact retrieval, and recent memory problems were solved pre-training by calculation, and post-training by fact retrieval. Problems were further labeled by whether they were part of the training set or not. Table 2.5 shows the frequencies of the strategy reports, broken down by training and initial strategy. As would be expected, a greater proportion of calc-mem problems appeared in the trained group than in the untrained group. Figure 2.7 shows the reaction times and accuracies for these problems.

	Initially Memorized		**Initially calculated**	
Training	remote mem	Mem->calc	calculated	recent mem
Untrained	*M*=93.4%, min=70%, max=100.00%	*M*=6.6%, min=0%, max=30%	*M*=79.5%, min=26.7%, max=100%	*M*=20.5%, min=0.00%, max=73.3%
Trained	*M*=97.2%, min=81.3%, max=100%	*M*=2.8%, min=0%, max=18.8%	*M*=50.67%, min=0%, max=88.2%	*M*=49.3%, min=11.8%, max=100%

Table 2.5: Frequencies of various strategies used by participants. Cells show means and ranges for each pre-post strategy, organized by training and initial strategy.

2.5.2.2 Strategy effects

A paired t-test was performed. There was a significant difference between the reaction times for calculated (M=0.86, SD=0.33) and memorized (M=0.66, SD=0.14) problems; $t(14.0)=3.39$, p=0.004, d=0.87. No significant difference was found in the accuracies for calculated (*M*=98.36, *SD*=1.60) and memorized (*M*=98.50, *SD*=1.41) problems; *t*(14.0)=-0.46, n.s.

2.5.2.3 Training effects

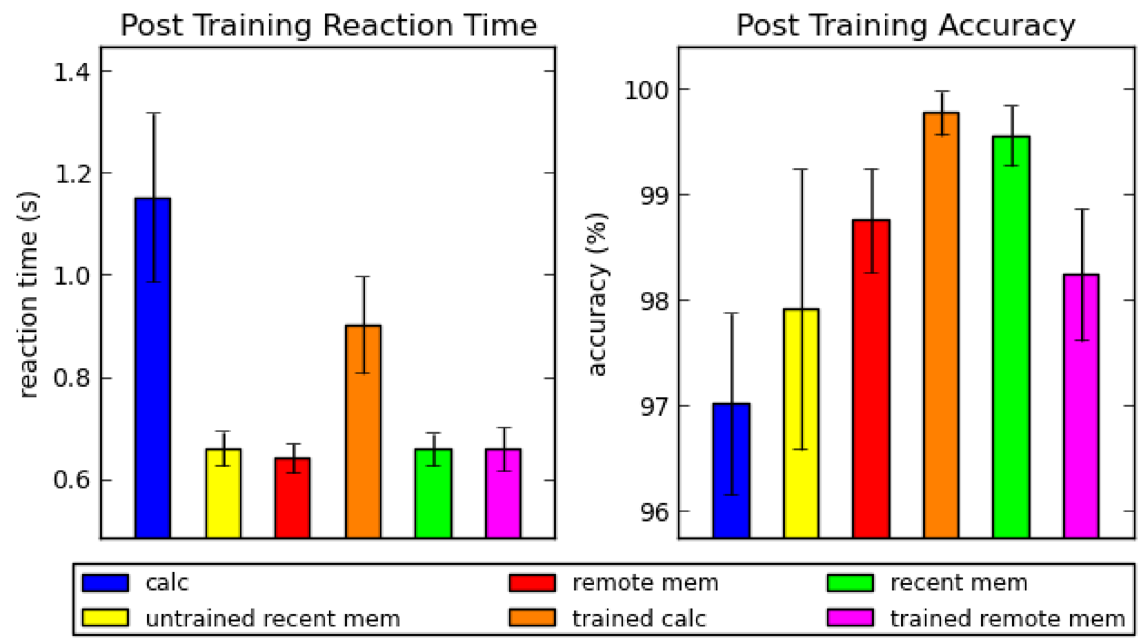

Figure 2.7: RTs and Accuracies for post training strategy conversions (Choice Task)

A paired t-test revealed an effect of training on RT, with a significant difference between the reaction times for untrained (*M*=0.81, *SD*=0.28) and trained (*M*=0.71, *SD*=0.20) problems; *t*(14.0)=2.27, *p*=0.040, *d*=0.59. However, no significant difference was found between the accuracies for novel (*M*=97.92, *SD*=2.27) and trained (*M*=98.90, *SD*=1.35) problems; *t*(14.0)=-1.54, n.s. 2x2 ANOVAs were also conducted to examine any interactions between strategy and training on ACC or RT. For RT, a significant relationship was found, with *F*(1, 14) = 7.55, *p*=0.016. No such interaction was found for accuracy, *F*(1, 14) = 3.50, n.s. The Training by Strategy interaction was driven by the fact that there was a larger strategy effect among the untrained problems, as in Experiment 1. Figure 7 shows these differences, with the calculated strategy broken into calculated and recent memory (calc->mem), as in the previous section.

2.6 Discussion

The objective of the above experiments was to develop and test a paradigm (Customized Arithmetic Training) that could address one of the main challenges of studying mental arithmetic, specifically inter-individual variability in strategy use. What may be solved through direct fact retrieval in one person may be solved by effortful procedural calculation in another. The CAT paradigm, through the use of individually tailored problem sets, successfully balanced strategy use across participants such that each participant relied on the same mixture of strategies (half calculation and half retrieval) at the start of the training program. Self-reported strategy was used to obtain the customized arithmetic sets, and the reliability and face validity of these measures was tested and found to be adequate when using either a voice production task (where participants speak the solutions aloud) or a choice task (where participants select the correct answer from a 2-item list using a button press), the latter task being more suitable for fMRI research, which was the ultimate goal of this thesis project.

There were five critical issues that were addressed in this experimental design. The first was the issue of the face validity of self-reported strategy. Memorized problems were found to have smaller pre-training sums than calculated problems and were also solved more quickly than calculated problems, indicating that the self-reports were valid. The second issue was reliability – specifically whether self-reported strategy would remain consistent both within and between task. Strategy remained consistent both within and between tasks (as assessed by % of problems being solved by the same strategy). The third issue was to determine whether a task suitable for fMRI (e.g., a choice task) could be used to create the CAT sets, and this was indeed the case with Experiment 2 producing results consistent with those of Experiment 1 (where the voice task was used). The fourth issue was to assess individual differences in strategy use as well individual differences in learning rates resulting from the training problem. Finally, the fifth aim was to evaluate the effectiveness of the problem finding algorithm that was used to generate the CAT sets.

In terms of face validity, memorized problems had smaller pre-training sums than calculated problems and were also solved more quickly than calculated problems.

However, a critical finding was that reaction times that were 'slow' and 'fast' varied greatly from participant to participant, as did the sums. In other words, measures of reaction time and sum are only useful in the context of a single participant's data, and could explain why problem size has been shown to be a poor predictor of strategy and reaction time when used as an average across a group of participants (LeFevre et al., 1996). Without using the CAT technique, raw measures of reaction time and sum are taken out of context, and in essence are a 'one size fits none' solution.

Regarding reliability, strategy remained consistent both within and across tasks (as assessed by % of problems being solved by the same strategy). However, one specific type of strategy shift did commonly occur – which is the conversion of calculated problems to memorized problems. This occurred mostly due to training, but also happened within the context of the calibration session when the same problem within a short (e.g., 3-4) amount of trials. However, since the memorization of a calculated problem is to be expected under these circumstances, this also speaks to the utility of self-reported strategy (if, for example, strategies were shifting from memorized to calculated, there would be no cause for such optimism).

Crucially, good between-task reliability for the strategy reports was found during Experiment 1, so the choice task (which is more suitable for fMRI research) was used on its own in Experiment 2. When the choice task was used to calibrate the CAT sets, problems in these sets had similar attributes to those obtained in Experiment 1 with the voice task, as well as similar learning rates. This indicated that the choice task could be used for the fMRI experiments featured in Chapters 3 and 4.

2.6.1 Limitations and improvements to the paradigm

Regarding learning rates, the training schedule used in the above experiments (5 days, 10 repetitions a day of 20 MEM and 20 CALC problems) resulted in about half the trained calculated problems being converted to memory post-training. Given one of the main goals of this project was to study the neural correlates of this strategy shift, greater learning rates were desired, so that for each participant an adequate amount of recent memory trials are occurring. Two steps were taken to increase the rate of conversion from calculation to fact retrieval. Firstly, the number of trained memorized problems was decreased from 20 to 10, which allowed for more repetitions of each problem per day (12 instead of 10) in about the same amount of time. Secondly, the training schedule was extended by adding a day of training (from 5 to 6 days).

The final critical issue in this pair of experiments was to evaluate and potentially improve the CAT calibration algorithm. The algorithm used an incremental approach to operand selection, which meant that for most problems, operands were fairly close in size to each other (e.g., 5 + 6, 34 + 36). This could be solved via the random selection of operands (which would allow for a greater variety in the problems presented to the participant), and this change was implemented for the fMRI experiment detailed in Chapters 3 and 4. Furthermore, it was found that at the single participant level, problems with high sums tended to be solved by calculation whereas smaller problems tended to be solved by memory. Thus, the algorithm was altered such that this 'tipping point' between memory and calculation could be established for each participant and used to inform the problem search process during the calibration phase (for more detail, see Chapter 3 - Methods).

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Chapter 3

3 Neural correlates of arithmetic fact retrieval

3.1 Introduction

The ability to retrieve arithmetic facts from memory (i.e., to know the answer to an arithmetic problem without having to calculate it) is an important aspect of mathematical proficiency, which in turn has been linked to many positive health, social, and cognitive outcomes (Imbo, Duverne, & Lemaire, 2007; Parsons & Bynner, 2005). Areas in and around the parietal cortex have long been associated with mental arithmetic (Gerstmann, 1940; Henschen, 1919), and recent studies have begun to examine the neural correlates of arithmetic fact retrieval. Specifically, the brain regions associated with fact retrieval have been investigated directly by studying different strategy uses (retrieval vs. procedural calculation) and indirectly by examining the effect of training (practiced vs. unpracticed problems). Both of these comparisons identify similar networks of brain regions, with retrieved and/or rehearsed problems associated with activity of the ventral posterior parietal cortex (vPPC), notably the left angular gyrus (AG) and unrehearsed and/or calculated problems associated with widespread activity in lateral and medial frontal cortex as well as the dorsal posterior parietal cortex (dPPC), notably the intraparietal sulcus (IPS) (Delazer et al., 2003; Grabner et al., 2009). Such findings showing similar brain regions associated with the use of retrieval strategies and trained problems raise the question of whether training effects are analogous to a shift in strategy from the use of procedural calculation to a reliance on fact retrieval, and if this is the case, whether recently learned facts draw on the same memory systems as facts that have been known since early in life (recent vs. remote facts).

3.1.1 The influence of training

The first fMRI study to investigate functional brain activation changes associated with learning arithmetic compared trained and untrained multiplication problems (Delazer et al., 2003). During training, participants repeatedly solved the same set of multiplication problems across several sessions over the course of a week. Following training, participants solved trained and novel, untrained problems as changes in brain activity were measured by means of fMRI. Greater activation was shown for trained versus untrained problems in the left angular gyrus (AG), inferior temporal gyrus, and anterior cingulate gyrus. The reverse contrast (i.e., untrained > trained problems), revealed widespread frontoparietal activation. This general pattern of results – widespread fronto-parietal activation for untrained problems and focal activation in the left angular gyrus and the cingulate gyrus for the trained problems – has since been replicated (Grabner, Ansari, et al., 2009; Ischebeck et al., 2006; Ischebeck, Zamarian, Egger, Schocke, & Delazer, 2007; for a more detailed review, see Zamarian, Ischebeck, & Delazer, 2009). More broadly, these results are consistent with evidence from the study of skill acquisition (e.g., motor learning) which suggests that the emergence of expertise is associated with a shift from more domain-general prefrontally-mediated processing to more domain-specific posterior cortical processing (Poldrack, 2000). In the case of mental arithmetic, this may reflect a diminishing reliance on working-memory intensive calculation-based strategies to increased reliance on direct retrieval of specific arithmetic facts (Delazer et al., 2003; Imbo & Vandierendonck, 2008). Nevertheless, this view remains largely untested because the strategy used to solve each problem has never been measured in these training studies.

3.1.2 The influence of strategy (retrieval vs. calculation)

The neural correlates associated with different strategies in mental arithmetic are not well understood, however a recent study has examined differences between solving through fact retrieval and solving through procedural calculation (Grabner, Ansari, et al., 2009). In this study, a group of adults were presented with a variety of arithmetic problems (all four arithmetic operations) and were asked to indicate which of two subsequently presented solutions was correct. Following scanning, participants were shown the problems they had just completed while in the scanner and asked to indicate whether they had solved each problem by memory or via calculation. Memory problems were the problems where a solution immediately came to mind without any intermediate steps, such as when someone is asked "what is the answer to 2 + 2" and "4" retrieved from memory without any conscious effort. If any other steps were required, such as counting, and/or the retrieval of intermediate solutions, then the problems were labeled as calculated. Brain images obtained were then sorted based on these strategy self-reports. Activity during self-reported calculation problems was greater than activity during self-reported retrieval problems in a widespread frontoparietal and insular network. Conversely, activity during self-reported retrieval problems was greater than activity during self-reported calculation problems exclusively in the left angular gyrus (AG). Interestingly, these activation patterns very closely mirror those seen in previous work (as noted above) for untrained and trained problems, respectively, suggesting that training effects might be explained by the fact that untrained problems are more likely to be solved via effortful calculation and trained problems via retrieval from memory.

3.1.3 Temporal gradients affecting semantic memories

If training effects are indeed due to differential usage of a fact retrieval strategy, then the time at which these facts were encoded must also be considered. In one study of semantic memory, participants were asked a series of questions relating to news items that spanned a 30-year period. Regions in the medial temporal lobe, specifically the hippocampus, temporopolar cortex, and amygdala exhibited lower levels of brain activity, for older rather than newer memories, whereas regions in the frontal lobe, temporal lobe, and parietal lobe exhibited the opposite pattern (Smith & Squire, 2009). This suggests that these structures play a time-dependent role in semantic memory. This has implications for the study of training effects and mental arithmetic, because problems that have been memorized through training would not be expected to show the same profiles of activity as problems that have been known since the study's outset. In the study of calculation vs. retrieval mentioned above, problems that had been memorized since before the study began (e.g., remote memories) were contrasted against procedural calculation problems (Grabner, Ansari et al., 2009). This is different than the contrast commonly featured in training studies, where problems that were memorized through training (e.g., recent memories) are contrasted against procedurally calculated problems (Delazer et al., 2003). If the brain activation that is present during the retrieval of a semantic memory is affected by a temporal gradient, then it should be the case that recent and remote memories are not equivalent in terms of the extent of activation in the brain regions associated with semantic memory. This prediction has yet to be investigated in the context of arithmetic fact retrieval.

3.1.4 Current Study

The ultimate goal of the current study was to examine the neural correlates of arithmetic fact retrieval by conducting a joint examination of strategy and training effects. To do this, the current study adopted the customized arithmetic training (CAT) protocol described in the previous Chapter. Individually tailored problems sets were generated for each participant such that half the problems in the set were solved through fact retrieval and the other half were solved through calculation. After obtaining these sets, a subset of these problems was then rehearsed by participants over a six-day period through a web-based training program. Following training, participants underwent an fMRI session in which they solved both the trained and untrained problems. After the scan they provided a self-report indicating which strategy they used to solve each problem (Grabner, Ansari, et al., 2009). In this way, strategy use was tracked pre- and post-training. This allowed for the identification of three important problem types; remote memories (i.e., problems whose solutions had been memorized since before the study began), recent memories (i.e., calculated problems that were memorized through training), and calculated problems (i.e., problems that were solved through procedural calculation both pre- and post-training and were not part of the training set).

This investigation was carried out with three specific aims in mind. The first aim was to explore the difference between the neural correlates of remote memories and procedural calculations. The second aim was to determine whether the training effects observed in previous literature could be attributed to a strategy shift from procedural calculation to fact retrieval. Finally, the third aim was to investigate whether neural activity during fact retrieval was affected by a temporal gradient.

3.1.5 Hypotheses

Regarding the first aim, though the comparison of procedurally calculated problems against memorized problems has been carried out once already (Grabner, Ansari et al., 2009), the balance of strategies was not controlled for on a participant-by-participant basis, nor was the reliability of each participant's strategy report assessed. Thus, a replication of this contrast with more methodological control (as is being done in the current study) was of utmost importance, as this would produce a clearer picture of the differences between remote memories of arithmetic facts and procedural calculations. It was hypothesized that the contrast of remote memory > untrained calculated problems would produce activity in regions beyond (and including) the left AG.

Regarding the second aim, results from Chapter 2 indicated that training calculated problems would cause a subset of these problems to become memorized (and not just calculated more efficiently) indicating a qualitative shift in strategy to fact retrieval. It was predicted that if training effects observed in previous studies can be explained by a shift in strategy, then the contrast of recently memorized problems > untrained calculated problems should produce results consistent with what is found in training studies, namely greater activation of the angular gyrus and the anterior cingulate cortex (Delazer et al., 2003, 2005; Ischebeck et al., 2006; Grabner et al., 2009). Finally, the third aim was to look for any evidence of a temporal gradient which might affect neural activity during the retrieval of arithmetic facts. The current study design allowed, for the first time, for the separation of newly learned arithmetic facts from facts that had been known since before the study began. Studies investigating temporal gradients affecting neural activation during the retrieval of semantic memories have shown that older memories are associated with activity in regions in the frontal lobe, temporal lobe, and parietal lobe (Smith & Squire, 2009). The parietal structure most commonly associated with arithmetic fact retrieval is the AG, thus it would be expected that recent memories would show greater AG activation than would remote memories. However, as previously mentioned, the neural correlates of fact retrieval are not well understood, so it was also predicted that other structures might be shown to play a time-dependent role in arithmetic fact retrieval.

3.2 Methods

3.2.1 Participants

20 adults between the ages of 23 and 30 (*M*=26.7 yrs, *SD*=2.6 yrs) participated in this study. All participants (12 men, 8 women) gave informed consent consistent with the

policies of the Human Subjects Research Ethics Board at the University of Western Ontario.

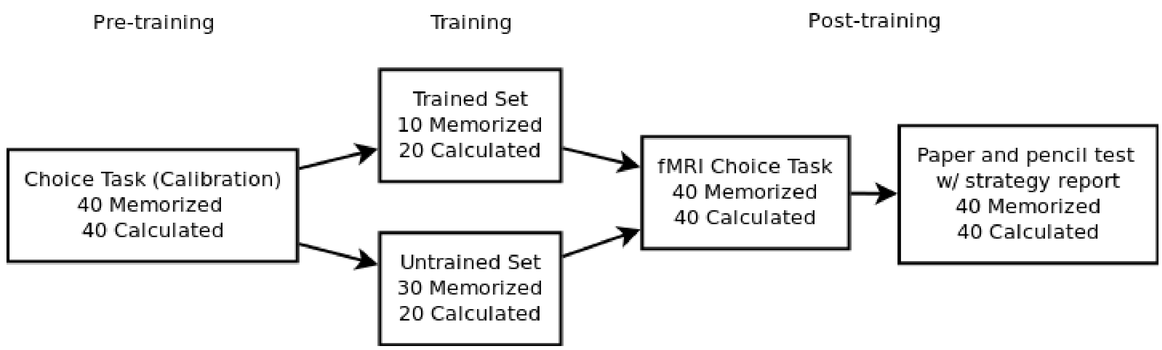

Figure 3.1: Flowchart of experimental procedure

3.2.2 Experimental procedure

3.2.2.1 Pre Training - Calibration

Participants were first introduced to the distinction between a memory-based and a calculation strategy. They were told that if a solution came to mind immediately after they viewed a problem, it should be classified as memorized. If they required any intermediate steps to solve the problem, it should be classified as calculated. After it was clear they could accurately apply this distinction when reporting their strategy use, calibration began.

Each trial in the calibration session consisted of an arithmetic problem followed by a self-report of the strategy that was used to solved said problem. Participants were presented with an addition problem for 2s (all problems were addition problems with sums less than 100). After the 2s had elapsed, the problem remained onscreen but two other numbers appeared beneath it: one was the correct solution, the other a distractor. Participants were asked to solve the problem without looking at the solutions, and then select by means of a button press the correct solution from among the two alternatives. Finally, participants verbally reported whether they solved the problem using a calculation or retrieval strategy, with the experimenter electronically recording each self-report by means of a keyboard entry. This process repeated until 40 MEM problems and 40 CALC problems were found for each participant. Each problem was shown twice to ensure that the strategy report was consistent, and the ordering of problems was pseudo-randomized such that the same problem never appeared twice in a row. Problems which were solved incorrectly, or which had an inconsistent strategy report were excluded from the final set.

The problem search algorithm functioned as follows. The first problem presented had small operands (e.g., 2 + 3) and these were gradually increased until the two digits added to no more than 100. Then, the size of the operands was decreased again until they were in the single digit range. This gave the program the ability to obtain an initial estimate of the size of an individuals' MEM and CALC problems as well as the most common operands involved. Using this information, potential CALC and MEM problems were then generated and presented. Throughout this process, problems with randomly selected operands were occasionally presented to the participant to provide more information (e.g., average sum and common operands for a given problem type) to the algorithm to assist in the search process.

Each problem had a distractor list assigned to it from which potential distracters were drawn. The distractor list was determined based on parity and sum in order to provide distractors that are similar enough to the actual solution that guessing did not take place (Ischebeck et al., 2006). When the parity of both operands was matched, a distractor of +-2 was part of the list. When the parity was mixed, a distractor of +-1 was part of the list. This was done to prevent participants from using the parity of the operands to determine the parity of the solution, without actually solving the problem itself. When the sum was greater than 30, a distractor of +-10 was part of the list. This was done so that participants could not determine the solution by examining only the first digit in any of the 2-digit problems. For each problem, all plausible distractors were randomly selected from such that participants would not come to expect a certain type of distractor based on the size and parity of the operands. For instance, for the problem "34+36", potential distractors would include +-2 and +-10. Thus, for any given presentation of "34+36", the participant might see 68, 72, 60, or 80 as the distractor.

3.2.2.2 Training

20 of the CALC problems and 10 of the MEM problems that had been identified in the calibration stage were assigned to training. Problems were pseudorandomly assigned such that sums were comparable across the trained and untrained sets. Pilot testing indicated that participants memorize about half of the CALC problems over the course of the 6 day training period, while MEM problems remain MEM problems, yielding a set of approximately 10 MEM problems, 10 CALC problems, and 10 CALC-MEM (e.g., recently memorized) problems prior to fMRI scanning.

Training took place in the participant's home using their personal computer. Participants visited a website which guided them through the training process. Each day, for 6 days, participants solved 12 repetitions (in random order) of their 30 training problems. The problem was presented onscreen and the participant typed the solution using the computer keyboard. Participants were given feedback when an error was made and had to solve the problem again. Participants solved 420 problems per day, plus any problems which were repeated due to error. Reaction time, accuracy and the solution inputted by each participant for each trial from the participant's training was recorded on the web server. Compliance was assured by checking that participants completed their 420 trials each day. No participants were excluded due to reasons of non-compliance.

3.2.2.3 Post training fMRI

The task in the scanner consisted of the same arithmetic choice task used in the calibration session, but with the strategy report omitted. As before, the problem remained onscreen for 2s, at which point the distractors appeared. Unlike the calibration session, these remained onscreen for 5 seconds regardless of when the participant responded. Each trial was separated by a variable ISI which ranged between 5 and 7 seconds to introduce jitter into the timeseries. 20 distinct ISIs (one for each trial) were used which averaged to 6s and were distributed randomly throughout each run. Each problem from both the trained and untrained sets of problems was shown to the participant twice, in random order.

Following the fMRI session, strategy self-reports were obtained by means of a paper and pencil method (Grabner, Ansari, et al., 2009). Participants were presented with a list of the problems they saw in the scanner and asked to solve them one last time – so again both trained and untrained problems were presented to the participant (in a randomized order, different from the order they appeared in the scanner). After generating each solution, they indicated whether they used a MEM or CALC strategy. Problems were then labeled using this strategy information, which allowed for the identification of any shifts in strategy that had occurred since the calibration session. For instance, a calculated problem represented a problem that was not part of the training set, and was solved by calculation both pre and post training. A recently memorized problem, on the other hand, represented a problem that was part of the training set that was initially solved by calculation, but was solved by memory post training – in other words, a recently memorized arithmetic fact. Problems that were memorized pre and post training were labeled as remote memories when they were not part of the training set, and labeled as trained remote memories when they were.

3.2.3 Stimuli

During pre- and post-training, stimulus presentation was controlled using custom made Python scripts which made use of the Vision Egg stimulus presentation library (Straw, 2003). Stimuli were displayed in white font on a black background, with a font size of 64pts. During the training stage stimulus presentation was controlled using a custom website written in Javascript and HTML, with a font size of 16 pt.

3.2.4 fMRI data acquisition

Data was collected in 4 functional runs using event-related fMRI, followed by the acquisition of a structural image. Functional and structural images were acquired in a 3-T Siemens Tim Trio whole-body MRI scanner, using a Siemens 32-channel head coil. A gradient EPI T2* sequence sensitive to the BOLD contrast was used to acquire 38 functional images per volume, which were collected in an interleaved order (3 mm thickness, 80 × 80 matrix, TR = 2000 msec, echo time = 52 msec, flip angle = 78°) and covered the whole brain. Two hundred seventy-two volumes were acquired for each functional run. High-resolution anatomical images were acquired with a T1-weighted MPRAGE sequence (1 × 1 × 1 mm, T1 = 2300 msec, echo time = 4.25 msec, TR = 2300 msec, flip angle = 9°). Each functional run took 8 minutes to complete, and 6 minutes were required to obtain the anatomical image.

3.2.5 fMRI data preprocessing

All functional images were preprocessed using Brain- Voyager QX 2.4.1. The steps included slice scan time correction (cubic spline interpolation), correction for 3-D head motion (trilinear motion detection and sinc motion correction), and temporal high-pass filtering (GLM- Fourier 2 cycles). All runs had less than 3 mm overall head motion in any of the 6 directions of motion and were thus included in the analysis. Each functional image was then coregistered to the subject's anatomical image, transformed into Talairach space, and smoothed with a 6-mm FWHM Gaussian smoothing kernel.

3.2.6 Thresholding

Unless otherwise indicated, all statistical results were initially thresholded with an uncorrected *p* value of 0.005. Subsequently, the maps were corrected for multiple comparisons to a statistical level of $p < 0.05$ using the cluster level correction plugin built into BrainVoyager. A review of this approach to multiple comparison corrections can be found here (Forman, Cohen & Fitzgerald, 1995). This cluster correction resulted in a minimum cluster size of 20 functional voxels (3x3x3 mm voxel size).

3.3 Results - Behavioral

3.3.1 Calibration

3.3.1.1 Strategy

Pre-training behavioral results resembled those found in the previous Chapter, with memorized problems (M=0.80s, SD=0.16) being solved more quickly than calculated problems (M=2.03s, SD=0.77); $t(19.0)=8.15$, $p<0.001$, d=1.82. The memorized (M=31.32, SD=10.70) problems also had smaller sums than the calculated (M=54.85, SD=10.69) problems; $t(19.0)=21.68$, $p<0.001$, d=4.85. Figure 3.3 shows the extent of individual differences present in the current sample.

Though accuracy was high across all problem types, observed differences in accuracy were consistent with the findings of Chapter 1, with memorized problems(M=98.77, SD=1.00) being solved more accurately than calculated problems(M=96.81, SD=2.12); $t(19.0)=-4.56$, $p<0.001$, d=1.02.

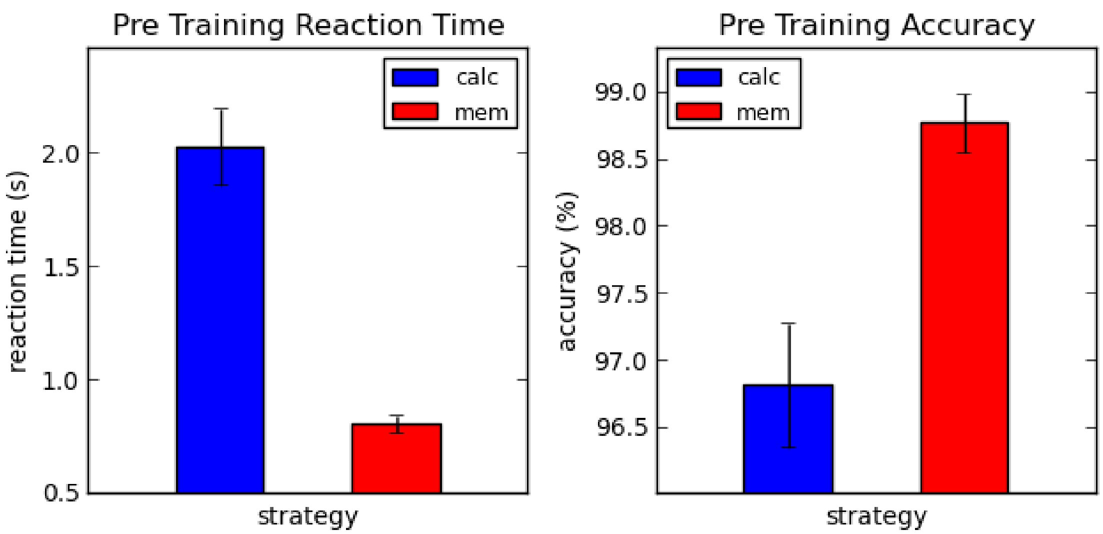

Figure 3.2: Bar charts showing average RT and ACC for the calibration session.

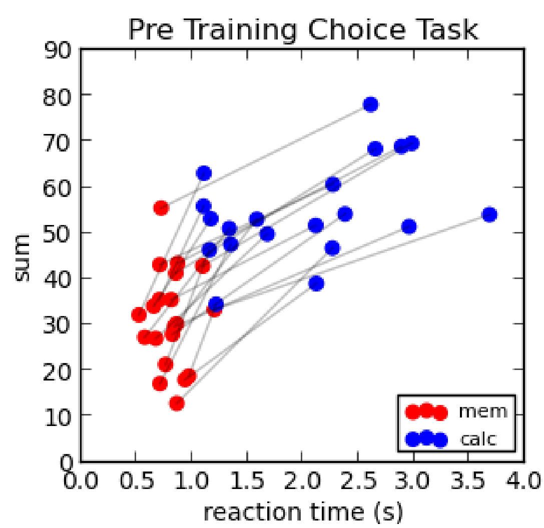

Figure 3.3: Scatter plot showing relationship between reaction times and sums for the calibration session. Red dots indicate memorized problems while blue dots

indicate memorized problems. Gray lines connect dots belonging to the same participant.

3.3.2 Post training fMRI

3.3.2.1 Strategy

On the basis of self-reported strategy use, problems were categorized as either calculated (calc-calc), remote memory (mem-mem), or recent memory (calc-mem). Calculated problems were defined as problems that were solved both pre- and post-training by procedural calculation. Remote memory problems were defined as problems that were solved both pre- and post-training by fact retrieval, and recent memory problems were solved pre training by calculation, and post training by fact retrieval. Problems were further classified on the basis of whether they were part of the training set or not. Table 3.1 shows the frequencies of the strategy report, broken down by training and initial strategy. As expected, the proportion of problems classified as calc-mem was greater among the trained than the untrained set. This Chapter focuses on the acquisition of arithmetic facts, thus for the remainder of this Chapter the following conditions will be analyzed: calculated (untrained), recent memory (trained), remote memory, trained remote memory.

Behavioral performance in the scanner (shown in Figure 3.4) was consistent with behavioral performance during the calibration session. Calculation (M=1.10, SD=0.31) problems were solved more slowly than remote memory problems (M=0.71, SD=0.11); $t(19.0)=6.39$, $p<0.001$, d=1.43, and also more slowly than recently memorized problems (M=0.74, SD=0.12); $t(19.0)=-6.00$, $p<0.001$, d=1.34. However, there was no difference in the time required to solve recently memorized problems and remote memorized problems; $t(19.0)=2.36$, n.s. As would be expected, trained remote memory problems were solved significantly faster than all other problems (M=0.67, SD=0.10). There were no significant differences in accuracy across the different problem types.

	Initially Memorized		Initially calculated	
Training	**remote memory**	**mem->calc**	**calculated**	**recent memory**
Untrained	*M*=91.6%, min=68.9%, max=100%	*M*=8.4%, min=0%, max=31%	M=68.6%, min=10%, max= 90%	M=31.4%, min=10%, max=90%
Trained	*M*=99.5%, min=90%, max=100%	*M*=0.5%, min=0%, max=10%	M=20%, min=0%, max=55%	M=80.1%, min=45%, max=100%

Table 3.1: Frequency of various strategy types obtained post-training.

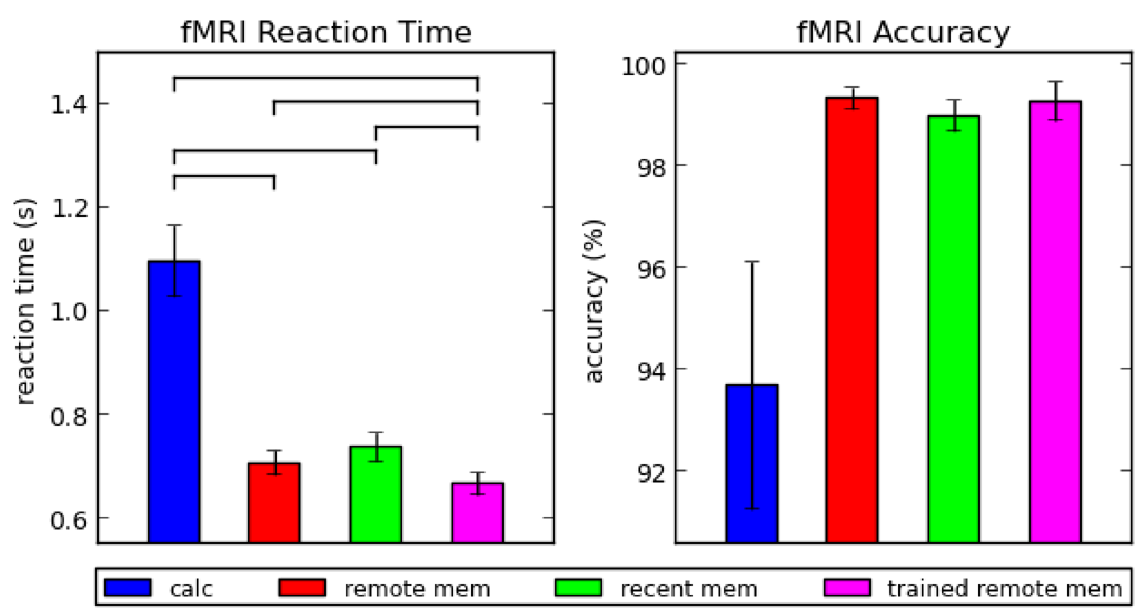

Figure 3.4: Bar charts showing reaction times and accuracies during fMRI scanner session.

3.4 Results - fMRI

Because one of the main interests in this study was the memory processes involved in arithmetic fact learning and retrieval, it was ensured that the temporal lobes were contained in the field of view (FOV) of our scans. Because parietal and frontal structures also have a well established role in mental arithmetic, these structures were included as well. This meant that for participants with larger brains, the ventral/posterior aspects of the occipital lobe was not completely imaged because they would not fit within the FOV provided at the imaging facility where this experiment was conducted. Given this, while activation occurring in these regions (i.e., BA 17, 18) will be reported, activity in these clusters could be spurious and thus interpretation of said activity will not be attempted.

3.4.1 Strategy (no training)

Strategy effects were examined by contrasting untrained calculated problems against untrained memorized problems. The effect of strategy among untrained problems can be observed in Table 3.2 and Figure 3.5. Greater bilateral angular gyrus activity was observed in the remote memory > calculated condition, as well as activity in a cluster which centered on the right anterior hippocampus, which extended anterior into the amygdala. Anterior to the activity in the right angular gyrus, greater activity was also observed in the intraparietal lobule, mostly in Brodmann area 40. Bilateral activation of the superior temporal gyrus (BA 38) was also seen. Results of the reverse contrast (calculation > remote memory) are shown in Table 2. These results are consistent with previous investigations of arithmetic strategy (Grabner, Ansari, et al., 2009), except for the hippocampal activation which marks a novel finding in adults.

Contrast between untrained memorized and untrained calculated problems

Remote memorized > calculated

Left Hemisphere					**Right Hemisphere**				
Structure	**x**	**y**	**z**	**Extent**	**Structure**	**x**	**y**	**z**	**Extent**
Angular Gyrus	-50	-60	22	2814	Angular Gyrus	53	-56	26	1736
					Anterior Hippocampus	20	-7	-15	596
Sup Temp	-39	11	-25	968	Sup Temp Gyrus	30	11	-28	799
					Inf Parietal Lobule	52	-27	20	2992

Calculated > remote memorized

Left Hemisphere					Right Hemisphere				
Structure	**x**	**y**	**z**	**Extent**	**Structure**	**x**	**y**	**z**	**Extent**
Intraparietal Sulcus	-27	-58	41	27425	Intraparietal Sulcus	27	-56	43	28734
Mid Frontal Gyrus / Insula	-34	18	17	37579	Mid Frontal Gyrus / Insula	32	18	18	31368
					Anterior Cingulate	23	42	-8	2363
Medial Frontal / Anterior Cingulate	-3	7	47						
Occiptal	-27	-83	-5	29479	Occipital	29	-74	-10	36691
Declive	-32	-57	-16	32644					
Thalamus/Brainstem	-2	-15	6	35597					

Table 3.2: x, y, and z coordinates indicate center of cluster. Extent indicates volume in mm^3 of each cluster.

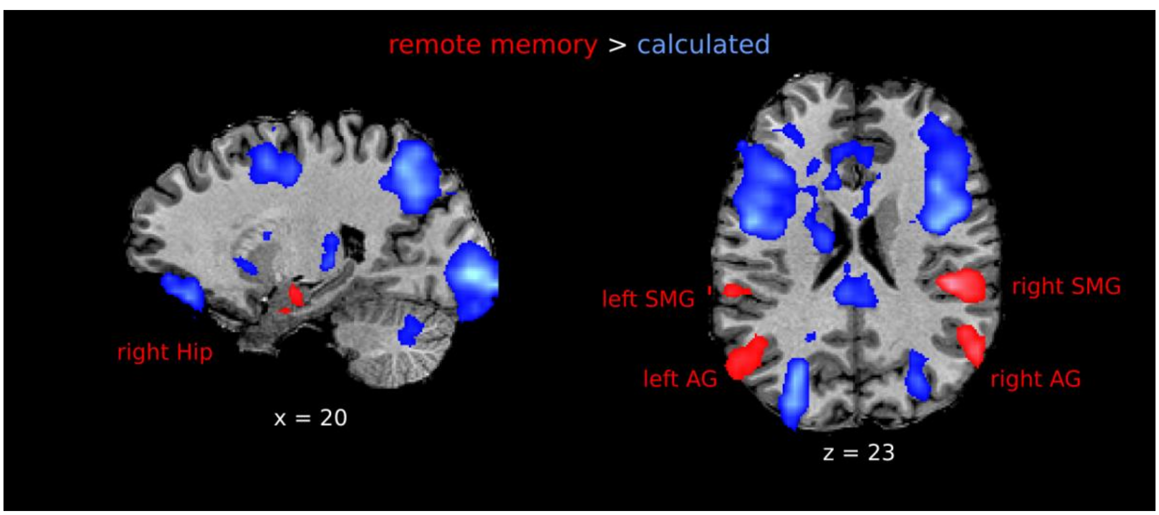

Figure 3.5: Contrast of remote memory > calculated. Widespread frontoparietal activation is seen for the calculated problems, while focal activation of left and right AG and SMG is seen for the memorized problems.

3.4.2 Training effects

Training effects were examined by comparing problems that were memorized through training against untrained calculated problems. The contrast of recently memorized > calculated problems (shown in Table 3.3) yielded a pattern of activation strikingly similar to the contrast of untrained memorized > calculated problems (shown in Table 3.2) - with bilateral angular gyrus and posterior cingulate activity associated with the retrieval of recently memorized problems and widespread frontoparietal activity associated with the solving of calculated problems. Absent from this contrast, however, was the cluster centered in the hippocampus.

Recently memorized problems (trained) compared with calculated problems (untrained)

Recent memory > calculated

Left Hemisphere					**Right Hemisphere**				
Structure	**x**	**y**	**z**	**Extent**	**Structure**	**x**	**y**	**z**	**Extent**
Angular Gyrus	-50	-59	26	2643	Angular Gyrus, Supramarginal Gyrus	52	-57	31	1601
					Supramarginal Gyrus	49	-28	22	596
Posterior Cingulate	-1	-49	28	1202					

calculated > recent memory

Left Hemisphere					**Right Hemisphere**				
Structure	**x**	**y**	**z**	**Extent**	**Structure**	**x**	**y**	**z**	**Extent**
Intraparietal Sulcus	-26	-59	40	12139	Intraparietal Sulcus	29	-53	44	16169
Insula, dlPFC	-38	23	9	8745	dlPFC	40	19	22	8255
					Caudate / Insula	9	7	6	14412
					vmPFC	26	41	-8	1414
Precentral Gyrus	-42	2	29	9153	Premotor Cortex	24	2	54	3102
Anterior Cingulate	-3	17	42	15409					
					Posterior Cingulate	0	3	27	568
Fusiform	-42	-57	-14	20524	Fusiform	51	-50	-9	713

Occipital	-32	-84	-1	19291	Occipital	29	-85	0	11557
Brainstem / Thalamus	-5	-17	1	10926					
Declive	-7	-75	-22	6845	Declive	35	-78	-18	931
Culmen	-2	-50	-7	1204					

Table 3.3: x, y, and z coordinates indicate center of cluster. Extent indicates volume in mm^3 of each cluster.

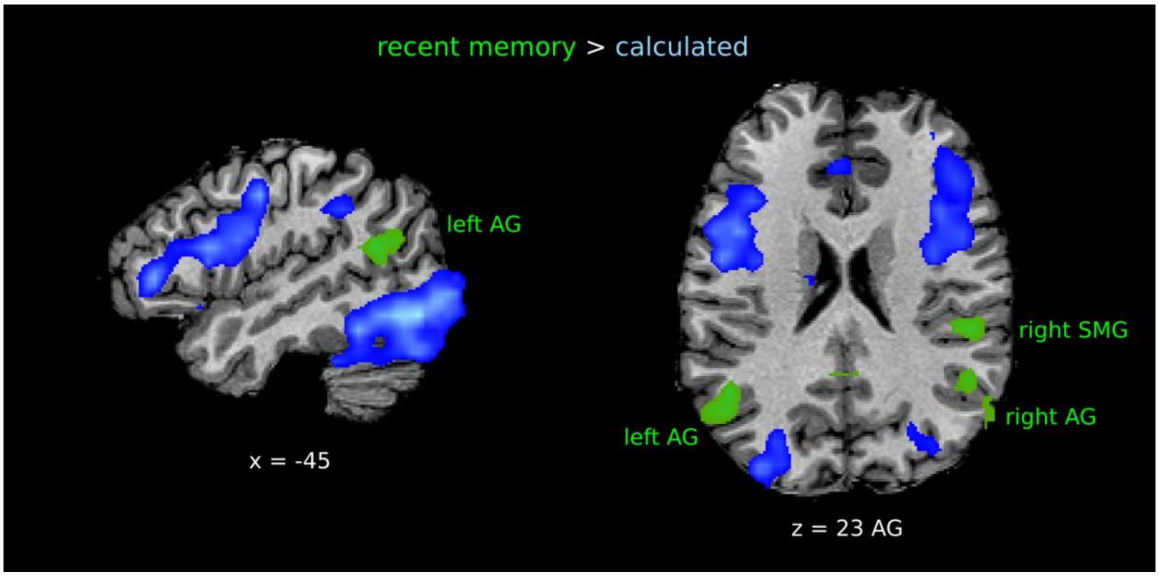

Figure 3.6: Regions of significant activity for the contrast of recently memorized problems > calculated problems.

3.4.3 Temporal gradients

The existence of a temporal gradient affecting neural activation during arithmetic fact retrieval was investigated by comparing recently memorized problems against problems that were memorized since before the study began. The contrast of recent memory > remote memory showed that remote memories were associated with more activity in a cluster in the left SMG, while a contrast of trained remote memory > recent memory showed that the trained remote memorized problems were associated with greater activity in the bilateral SMG and left AG (Figure 3.8). Familiarity, or perhaps ease of retrieval seemed to modulate the AG activity (even in the absence of a shift in strategy). Additionally, the recently memorized facts were associated with greater activation in widespread frontoparietal regions when compared to remote memories (both trained and untrained) – despite being reported as memorized and solved at roughly the same speed as a remote fact. Table 3.4 lists the clusters for these contrasts.

Lastly, a cluster in the right hippocampus was observed in the trained remote memory > recent memory as well as the remote memory > recent memory contrasts, but it did not survive cluster correction due to its small size. However, this cluster was located in an ROI identified by the memorized > calculated contrast shown in Table 3.2. Thus, beta weights for this ROI were extracted for trained memory and recent memory conditions (shown in Figure 3.7) and compared using a t-test. There was a significant difference between the beta weights for recently memorized (*M*=-0.60, *SD*=0.69) and trained memorized problems (*M*=-0.20, *SD*=0.53); *t*(19.0)=-2.58, *p*=0.018, *d*=0.58.

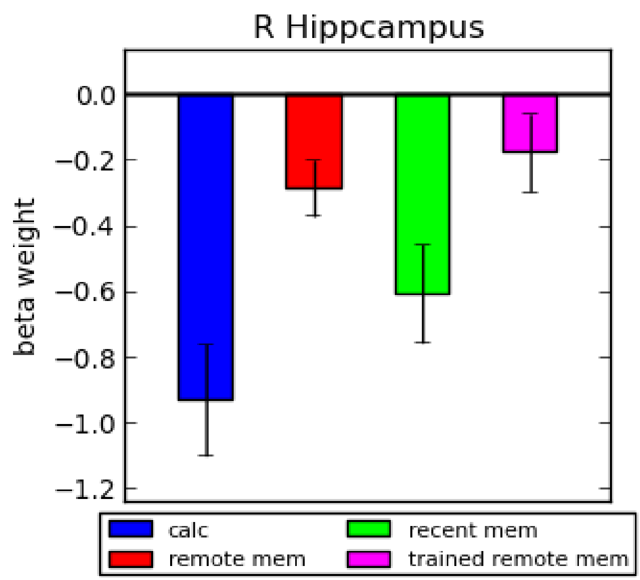

Figure 3.7: Beta weights for a cluster in right anterior hippocampus. Green bar shows recently memorized problems, pink bar shows trained remote memories.

Recent memories compared to remote memories and trained remote memories

remote memory > recent memory

Left Hemisphere					**Right Hemisphere**				
Structure	**x**	**y**	**z**	**Extent**	**Structure**	**x**	**y**	**z**	**Extent**
Supramarginal Gyrus	-63	-30	25	758					

trained remote memory > recent memory

					SMG, AG	54	-47	30	2021
					SMG / BA 40	55	-23	18	651

recent memory > trained remote memory

Left Hemisphere					**Right Hemisphere**				
Structure	***x***	***y***	***z***	**Extent**	**Structure**	**x**	**y**	**z**	**Extent**
Intraparietal Sulcus	-31	-57	42	19657	Intraparietal Sulcus	26	-61	42	15888
dlPFC	-45	8	31	11067	dlPFC	45	14	27	5453
Premotor Cortex	-25	0	59	3415	Premotor Cortex	27	-2	57	2505
Anterior Cingulate	-1	14	41	11633					
Insula	-31	17	4	1134					
Occipital	-29	-83	-8	11797	Occipital	25	-87	-7	8980
					Culmen	26	-57	-27	673
					Pyramis / Declive	2	-69	-24	2350

recent memory > remote memory

Left Hemisphere					**Right Hemisphere**				
Structure	**x**	**y**	**z**	**Extent**	**Structure**	**x**	**y**	**z**	**Extent**
Intraparietal Sulcus	-32	-57	40	16441	Intraparietal Sulcus	31	-55	39	5886
dlPFC	-44	20	26	6655	dlPFC	40	14	27	5128
Premotor Cortex	-20	2	52	5183	Premotor Cortex	22	-3	49	2151
Precentral Gyrus	-41	2	34	8166					
Insula	-32	17	2	1499					
					Anterior Cingulate	0	20	40	8168

Posterior Cingulate	-2	-19	26	2632					
Fusiform	-42	-55	-11	959					
					Occipital	24	-88	-7	5990
Thalamus	-10	-15	11	994	Thalamus	17	-20	11	960
					Caudate	11	0	11	736
					Declive	14	-64	-22	6245

Table 3.4: x, y, and z coordinates indicate center of cluster. Extent indicates volume in mm^3 of each cluster.

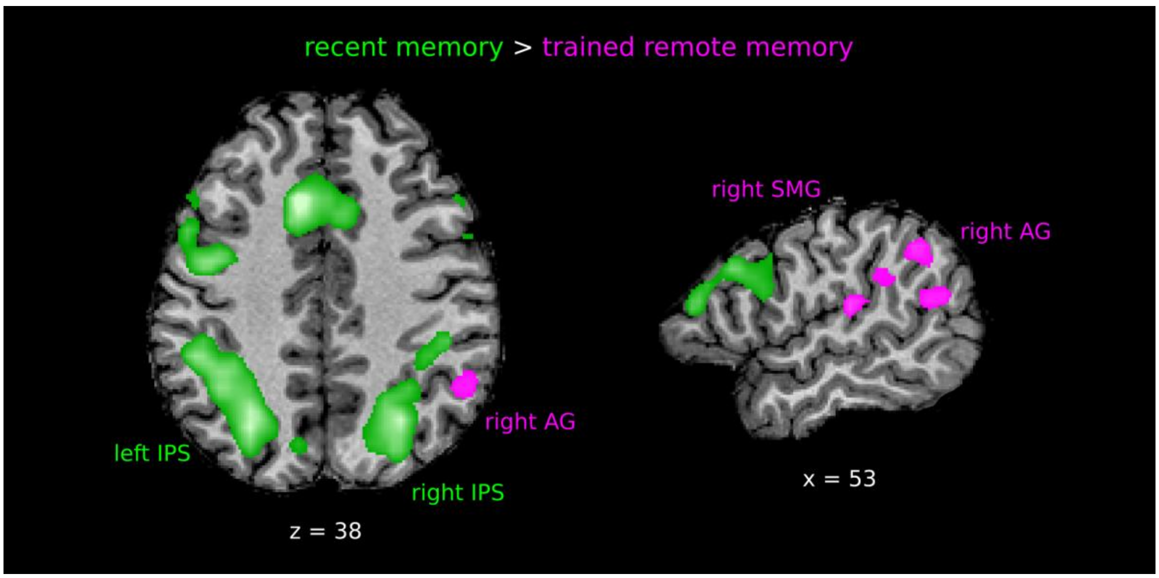

Figure 3.8: Regions of significant activity for the contrast of recent memory > trained remote memory problems.

3.4.4 Difficulty effects

Since other factors related to general difficulty, such as the sum of the addends, might have been modulating neural activity during mental arithmetic, it was necessary to evaluate the extent to which these factors affected activity in the conditions used in the previous analyses. In particular it was of interest to determine whether factors like reaction time and sum modulated activity in any of the regions implicated in either calculation or fact retrieval, notably areas which are part of the default-mode network (DMN), such as the AG or the hippocampus.

To examine difficulty effects two median split analyses were conducted – the first on reaction time (RT), and the second on sum (both are shown in Table 3.5, and in Figure 3.9). The purpose of this was to determine whether problems that took longer to solve (or had higher sums) were associated with greater activity in different brain regions than problems that were solved more quickly (or had lower sums). If this were the case, then it would suggest that the results shown in the previous section were more due to general task demands rather than differences induced by strategy and training.

The median splits were conducted on a subject by subject basis - for each subject, problems within a given strategy (i.e., remote memory, recent memory, untrained calculated) were divided into high and low RT categories. The high and low categories were then contrasted against each other using a whole brain analysis and the same statistical thresholding used in the other analyses (initial threshold $p<0.005$, cluster corrected to $p<0.05$). The same was done for high and low sums. This yielded three main results, the first being that activity in the remote memory condition was not modulated by either RT or sum. The second was that no reaction time or problems size effects in AG or the hippocampus were observed. Lastly, while AG was not affected, other frontoparietal regions were modulated by RT and sum in the untrained calculated and recently memorized conditions. Within the untrained calculation problems, a contrast of high RT > low RT yielded greater bilateral activation of the caudate, the right inferior frontal gyrus, the anterior cingulate, the left anterior insula, the left premotor cortex and the right occipital cortex. The reverse contrast resulted in greater activation in bilateral clusters in the posterior insula. Within the recent memory problems, the contrast of high RT > low RT yielded activity in the bilateral SPL and IPS, as well as bilateral activity in the fusiform and the anterior cingulate cortex. Left lateralized activity was seen in the insula, precentral gyrus and inferior frontal gyrus, while right lateralized activity was seen in the middle frontal gyrus. Interestingly, IPS, which is normally associated with calculation, was not modulated by RT among the calculation problems, but was modulated by RT during the recently memorized problems.

Sum also had a differential effect on IPS activity. Within the calculated problems, a contrast of high sum > low sum revealed activity in a single right posterior IPS cluster. Within the recently memorized problems, however, the contrast of high sum > low sum revealed no IPS activity, but did produce clusters in the left interior frontal cortex, the left anterior insula, and the bilateral occipital cortex.

These results suggest multiple factors which influence the engagement of the IPS and that these vary depending on the type of strategy being used to solve a problem. Specifically, IPS activity is modulated by sum (but not RT) in untrained calculated problems. The reverse is the case in recently memorized problems, where IPS activity is modulated by RT (and not sum).

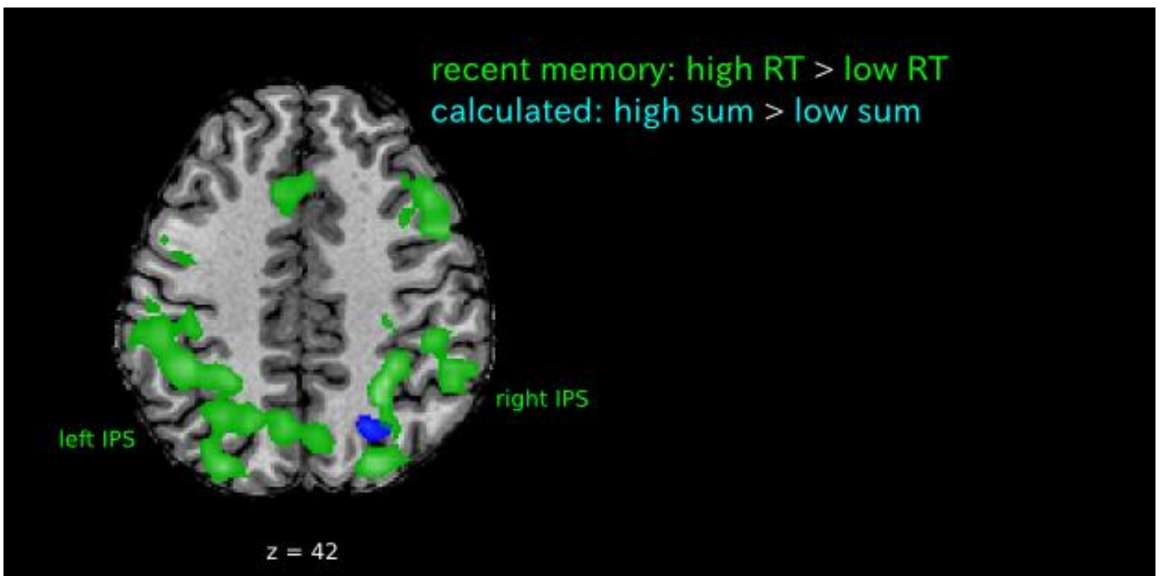

Figure 3.9: Results of median splits for recently memorized RTs (green) and untrained calculated sums (blue).

Median splits (RT and sum) for calculated and recent memory

calc low RT > calc high RT

Left Hemisphere					**Right Hemisphere**				
Structure	**x**	**y**	**z**	**Extent**	**Structure**	**X**	**y**	**z**	**Extent**
Posterior Insula	-36	-21	20	1143	Posterior Insula	38	-21	18	4440

calc high RT > calc low RT

					Interior Frontal	40	10	20	816
Caudate/Putamen	-7	-3	3	3989	Caudate/Putamen	21	13	2	6787
Anterior Insula	-30	18	2	965	Anterior Cingulate	0	15	44	9085
Premotor Cortex	-40	0	36	806	Occipital	-43	-68	-4	1249

recent memory high RT > recent memory low RT

Left Hemisphere					**Right Hemisphere**				
Structure	**x**	**y**	**z**	**extent**	**Structure**	**x**	**y**	**z**	**extent**
SPL/IPS	-32	-51	42	17412	SPL/IPS	33	-46	48	20184
Fusiform	-45	-55	-6	2369	Fusiform	36	-62	-16	3096
Insula	-35	17	1	1795					
Precentral Gyrus	-10	-16	64	15647					
Interior Frontal	-43	11	26	10373					
					Mid Frontal	39	28	21	20958
					Anterior Cingulate	0	24	37	3699
Occipital	-31	-88	0	1262	Occipital	41	-80	3	718
Declive	-34	-74	-17	988					

recent memory high sum > recent memory low sum

Left Hemisphere					**Right Hemisphere**				
Structure	**x**	**y**	**z**	**extent**	**Structure**	**x**	**y**	**z**	**extent**
Inferior Frontal	-43	0	19	588					
Insula	-30	19	9	606					
Occipital (BA 18)	-28	-88	-1	6772	Occipital	16	-97	4	1402

Occipital (BA 19)	-24	-82	38	1148					
Culmen	-28	-60	-26	1949					
calc high sum > calc low sum									
					Posterior IPS	23	-61	37	857

Table 3.5: x, y, and z coordinates indicate center of cluster. Extent indicates volume in mm^3 of each cluster.

3.5 Discussion

The objective of the current study was to examine the neural correlates of arithmetic fact retrieval by conducting a joint examination of strategy and training effects. The CAT protocol developed in Chapter 2 was used to generate individually tailored problems for each participant such that half the problems were solved through fact retrieval and the other half were solved through calculation. After obtaining these sets, a subset of these problems was then rehearsed by participants over a six-day period through a web-based training program. Following training, participants underwent an fMRI session in which they solved both the trained and untrained problems, after which they provided a self-report indicating which strategy they used to solve each problem (Grabner, Ansari, et al., 2009).

The current study explored three main issues. The first was to compare untrained calculated and untrained memorized problems using the CAT protocol. Consistent with previous research, it was found that angular gyrus activity was greater when problems were solved by memory (Grabner, Ansari, et al., 2009), however relatively greater activity in the right anterior hippocampus was also observed in this contrast. The second issue was to determine whether training effects observed in previous research could be attributed to a difference between calculated and recently memorized problems. This was found to be the case, with widespread frontoparietal activity being greater during procedural calculation, and activity in the bilateral angular gyri and anterior cingulate being greater during the retrieval of recently memorized facts (e.g., calculated problems whose solutions became memorized through training). Finally, evidence of a temporal gradient was looked for by comparing recently memorized facts against those that had been known since before the study began. Notably, activation was greater in IPS, anterior cingulate, and frontal regions during the retrieval of recent versus remote arithmetic facts.

3.5.1 Strategy effects (fact retrieval vs. calculation)

The contrast of untrained memorized > untrained calculated problems yielded the expected AG activation, but also an unexpected finding; activity in the right anterior hippocampus. Until this study, greater medial temporal lobe (MTL) activity during arithmetic fact retrieval (versus calculation) has been observed many times in children, and only once in adults. This has led to the widespread belief in a developmental difference in what brain structures are necessary for adults and children and adults to perform this operation (Cho et al., 2012; Cho, Ryali, Geary, & Menon, 2011; Rivera, Reiss, Eckert, & Menon, 2005). The present results, which do show an association between greater activity in the hippocampus and fact retrieval in adults, suggest that this account may need to be revised.

3.5.2 Training effects

As expected, training caused a shift in strategy use from calculation to fact retrieval for most of the problems in the training set. This training-induced change in strategy was associated with widespread frontoparietal activity during calculation and more focal activation of the ventral PPC (bilateral AG and right SMG) during retrieval of newly learned facts. In other words, the contrast of calculated problems against recently memorized (e.g., formerly calculated) problems produced a similar result to the contrast of calculated problems against problems that were memorized since before the study's outset (Table 3.4). This finding was consistent with the results of previous studies of training, which assumed that they were also comparing calculated problems against problems whose solutions had recently been memorized (Delazer et al., 2003, 2005; Grabner, Ischebeck, et al., 2009; Ischebeck et al., 2006, 2007).

3.5.3 Temporal gradients

Temporal gradients affecting neural activity during fact retrieval were also examined. While the comparison of recent and remote arithmetic facts indicated no differences in activity in the right or left angular gyri (contrary to prediction), the recently learned facts were associated with more widespread frontoparietal activity than the previously known facts. This suggests that the recently acquired facts may be at a putative halfway point between fully memorized and calculated problems. However, because the participants did report using fact retrieval for both the recent and remote memories (which, critically, were matched in terms of reaction time), the fact that the recent memories were still associated with more IPS activity than remote memories adds some nuance to the role of the IPS in calculation, which is typically associated with quantity manipulation (Dehaene, Piazza, Pinel, & Cohen, 2003). Specifically, it would not be expected that the retrieval of a recently memorized fact would require any manipulation of quantity, yet IPS activity was higher in the recent memory condition as compared to the remote memory condition. Thus, accounts of IPS associations with mathematical skill may need to be revised to include fact retrieval as well as quantity manipulation. Furthermore, hippocampal activation was greater for remote rather than recent memories, which, like the other brain activity observed in the contrast of recent and remote memories, is the reverse of the pattern expected for semantic memories (Smith & Squire, 2009), which raises questions regarding the role the MTL might be playing, and more, broadly, the nature of arithmetic facts in general.

3.5.4 Interpreting the MTL activation

The hippocampal activity observed in this study raises the question of why previous research on adult participants has not produced a similar result. Only one arithmetic training study (which used novel problem types, e.g., arithmetic operations that were contrived for the purposes of that study), did find evidence of greater MTL activation in the trained as compared to the untrained condition (Delazer et al., 2005). The remaining adult training studies have not uncovered any evidence of hippocampal associations with arithmetic fact retrieval, and the results of the present study can explain why this is. Recently learned memories do not differ significantly from calculated problems in their degree of hippocampal activation. It is only when comparing memorized problems that have been known since before the study began against calculated problems that differences in hippocampal activity were observed. To date, only one study (Grabner, Ansari, et al., 2009) has performed such a contrast, and the reliability of the strategy reports was never assessed, nor was the frequency of each strategy balanced between participants. Both of these factors could have decreased the statistical power of the study. Interestingly, the temporal gradient observed in the current results is inconsistent with Smith & Squire (2001), which showed the reverse pattern – with older memories associated with greater MTL activation MTL than newer memories. It appears, therefore, that arithmetic facts do not fit the mold of semantic facts.

3.5.5 How arithmetic facts are stored

If not a semantic association, then what association does MTL activation have with arithmetic fact retrieval? One possibility is binding - arithmetic facts can be operationalized as items (the numbers) bound together in a particular context (the operation). The MTL has been shown to be necessary for the binding of items together in contexts (Cohen & Eichenbaum, 1993; Cohen, Poldrack, & Eichenbaum, 1997; Eichenbaum & Cohen, 2001), which is a key aspect of episodic memory. Viewed from a relational perspective, each arithmetic fact is a set of items (numbers) that are bound together in a given context (the operation being performed). This is not to say that 2+2=4 is an episodic memory. Rather, that episodic memories and memories of arithmetic facts may share a common feature (binding), which is also associated with MTL activity.

Whatever the association, the present data are consistent with the idea that the hippocampus acts in concert with parietal structures, which have long been associated with mental arithmetic (Henschen, 1919; Gertsman, 1940). To understand the reason why the IPS may be activated in calculated as well as in recently memorized problems (compared to remote memories), current theories on parietal contributions to episodic memory can be considered. Recent work on the parietal contributions to memory has resulted in a 4-way distinction (Hutchinson et al., 2012). This conceptualization divides the posterior parietal cortex into dorsal and ventral halves, with the AG and SMG/TPJ making up the ventral PPC, and the lateral aspects of the IPS making up the dorsal PPC.

Both ventral and dorsal structures have been suggested to play a part in retrieval, but take on different roles (Cabeza, Ciaramelli, Olson, & Moscovitch, 2008). Specifically, it has been hypothesized that dorsal PPC (i.e., IPS) activity during retrieval may reflect the recruitment of goal-directed attention in service of performing retrieval tasks while ventral PPC (ie., AG, SMG/TPJ) engagement during retrieval may mark the reflexive capture of attention by mnemonic representations (Hutchinson, Uncapher, & Wagner, 2009). Recent work has further refined these distinctions – showing functional subdivisions according to either memory or attentional demands. Within the dorsal PPC, SPL is related to top-down attentional processes and IPS to goal-directed memory retrieval. Within ventral PPC, TPJ is related to bottom-up attention and AG/SMG to reflexive memory retrieval (Hutchinson et al., 2012).

These roles for AG and IPS are consistent with the memory demands involved in mental arithmetic. AG activity is associated with the automatic retrieval of an arithmetic fact, i.e., the solution to a problem such as 2 + 3 comes to mind without effort. Calculation, on the other hand, requires a more directed search. If a person does not know the solution to a problem such as 15 + 24, they must first determine which intermediate facts to retrieve from memory – i.e., the answers to 5 + 4 and 1 + 2. In this way, IPS activity may be associated with the search for and/or retrieval of arithmetic facts not immediately present in the displayed problem. Why, then, the increased IPS activity for recently memorized problems as compared to memorized problems that have been known for long periods of time? One possibility is that the six-day training program is insufficient to commit these facts to memory to such that they are effortlessly retrieved. Specifically, the factor that cues the participant to engage in retrieval may be different. While remote memory problems are retrieved automatically, recently memorized facts may be recognized as familiar, and this feeling of familiarity prompts a memory search. In this way, a retrieval strategy is used to solve the recent memory problems, but the act of retrieval is still more effortful than for a problem where the solution automatically comes to mind.

Another way to explain the IPS activity during recent memory retrieval would be parallel engagement of the both the retrieval and calculation processes. In other words, the recent memories would have been simultaneously activating the fact retrieval network and the calculation network. This would explain why for the contrast of recent memories > remote memories no difference was evident in the angular gyrus (in the service of retrieval), but additional IPS recruitment (in the service of calculation) was observed for the recently memorized problems. If this the case, then the IPS activity should have been modulated by the same behavioral and stimulus factors – namely reaction time and sum – in both calculated and recently memorized problems. However, this was not consistent with the results of the median splits performed on RT and sum. IPS activity was modulated by sum (but not RT) in untrained calculated problems, while in recently memorized problems IPS activity was modulated by RT (and not sum). Thus, there was a functional dissociation between the role of the IPS in calculation and the role of the IPS in retrieving recently memorized facts, which does not support the parallel engagement hypothesis.

3.5.6 Limitations

Given the known association between parietal structures and attentional processes, an attention mapping task may be useful when studying mental arithmetic, as this would allow for the identification of functional subdivisions in the parietal cortex. An attention mapping procedure (Bressler & Silver, 2010) where participants would track a rotating wedge while maintaining fixation on a central point, could be very useful because it allows, on a participant-by-participant level, for the establishment of the boundaries of visual field representations in posterior parietal areas such as IPS and SPL. If this were done in the context of an arithmetic experiment, the degree of overlap between activation for mathematical tasks and activation for more general attentional processes could be properly examined.

3.5.7 Future directions

While it has been demonstrated that the shift from widespread frontoparietal activity to focal AG activity is a result of a shift from effortful calculation to fact retrieval, the full range of training effects has not yet been examined. In the next Chapter, the modulation of parietal activity by strategy and training will be described by examining the conditions where no change in strategy is present. Previous work has shown that both training and strategy induce shifts in activation in these areas (Delazer et al., 2003; Grabner, Ansari et al., 2009). However, the interaction between the two has yet to be explored. For instance, will a trained memorized problem still draw on more angular gyrus activity than an untrained memorized problem? Or, does the level of AG activity only change when a shift in strategy is present? Furthermore, what will the effect of training be on problems that are still solved by procedural calculation after training?

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Chapter 4

4 Strategy-specific training effects

4.1 Introduction

In Chapter 3, the neural correlates of arithmetic strategy and the impacts of training were explored by focusing on arithmetic fact retrieval, specifically, recently learned arithmetic facts. However, memorizing the solution to a problem is not the only effect training might be expected to have. Rehearsing the retrieval process itself may decrease the amount of time necessary for an arithmetic fact to be retrieved, while rehearsing the act of calculation may serve to optimize the calculation process, even in the absence of a shift in strategy. These strategy-specific training effects have not been widely explored in neuroimaging studies, owing to the difficulty of tracking and balancing strategy use in the way that is afforded by the CAT procedure developed as part of this thesis (see Chapter 2). Because of this, it remains unclear to what extent activity in the neural systems underlying mental arithmetic can be modulated through practice.

4.1.1 Training

The observed effect of training on brain activation during mental arithmetic is largely driven by problems that were initially calculated being converted into problems that were solved by retrieval (Delazer et al., 2003, 2005; Grabner et al., 2009; Ischebeck, Zamarian, Egger, Schocke, & Delazer, 2007). It is conceivable, however, that this does not fully describe the impact training may have on the neural systems involved in calculation, specifically the training effects that might occur in the absence a shift in strategy. According to the triple code model, calculation is associated with activity in the perisylvian areas and the intraparietal sulcus, with the former being related to language-related demands of mental calculation and the latter being related to quantity manipulation (Dehaene, Piazza, Pinel, & Cohen, 2003). From this perspective, training might be expected to produce more focal activity in these task-specific regions due to optimization of these systems (Poldrack, 2000). However it was found in previous work that these regions were more active in the untrained rather than the trained condition

(Delazer et al., 2003). Thus, it remains unclear how strategy-specific training effects may modulate brain activity during mental arithmetic.

4.2 Current Study

The goal of the current study was to examine how fact retrieval and procedural calculation may be modulated at the neural level via training, even in the absence of a shift in strategy. Data obtained from the experiment described in Chapter 3 was used to examine this issue directly. Strategy self-reports (either memorized or calculated) were obtained both before and after training. Since this analysis was concerned solely with strategy-specific training effects, only problems whose strategies did *not* change were examined. In other words, only problems that were either memorized or calculated both before and after training were examined (whereas in Chapter 3 problems that were calculated, but became memorized were focused on). This allowed for the analysis of both the main effects of strategy as well as their interactions.

Regions of the brain that were differentially modulated by training (depending on strategy) were isolated by conducting a whole-brain test of the interaction between strategy and training. To do this, three analyses were performed. The first two analyses examined the main effects of strategy, and training, respectively. Finally, a two-way whole-brain test of the interaction between strategy and training was performed, and the beta weights of any clusters of activation were analyzed to determine the nature of the interaction effects revealed.

4.3 Hypotheses

It was predicted that the main effects of strategy would be similar to the comparison of untrained calculated and untrained memorized in Chapter 3, where it was found that clusters in the bilateral angular gyrus (AG), temporoparietal junction (TPJ), and right anterior hippocampus were more active during fact retrieval than during calculation. However, the effects of training were expected to modulate the main effects of strategy, altering magnitude of difference between the two conditions. Thus, while the effect of strategy was expected to be similar to those obtained in Chapter 3, they were not expected to be identical.

Some similarity was expected between the main effects of training and the results of previous training work, which are, as can be seen from the results reported in Chapter 3, primarily AG and anterior cingulate activity during the solving of trained problems as well as more widespread frontal and parietal activation during the solving of untrained problems (Delazer et al., 2003; Grabner et al., 2009; Ischebeck et al., 2006, 2007). However, this pattern was shown in the previous Chapter to be largely due to a difference in solving strategies (e.g., untrained calculated problems vs. trained recently memorized problems). Because the current design balanced strategy use (e.g., there are both memorized and calculated problems in the trained and untrained conditions), an identical pattern of results was not expected. Greater AG and anterior cingulate activity among trained problems represents a highly replicated finding, so this result was expected. However, it was also possible that activity in other regions not associated with training, such as the IPS or perisylvian regions (as predicted by the triple-code model) might be greater in the trained condition, owing to the fact that strategy use was balanced.

Finally, the interaction between strategy and training was expected to reveal regions in the brain whose activity was associated with the rehearsal of either the fact retrieval or the calculation strategy. The triple-code model would predict interactions in the perisylvian regions and intraparietal sulcus (IPS), because greater activation in these regions is associated with calculation. Specifically, training was expected to increase activation more for calculated than for memorized problems. For memorized problems, however, training was expected to have a greater effect in the basal ganglia and AG (Dehaene et al., 2003). Furthermore, the recommended updates to the triple-code model would also predict that frontal and cingular structures would be more affected by training in the calculated condition, and the bilateral AG would be more affected by training in the memorized condition (Arsalidou & Taylor, 2011).

4.4 Methods

Methods were identical to those used in Chapter 3.

4.5 Results - Behavioral

4.5.1 Main effect of Strategy

Calculated problems (*M*=1.03, *SD*=0.24) were solved more slowly than memorized problems (*M*=0.70, *SD*=0.10); *F(*1, 18)=47.21, *p*=0.001, η^2=0.18. Calculated problems were also solved less accurately (*M*=95.31, *SD*=7.97) than memorized problems (*M*=99.27, *SD*=0.90); *F(*1, 18)=4.62, *p*=0.045, η^2=0.44.

4.5.2 Main effect of Training

There was also a main effect of training on both reaction time and accuracy. Trained problems (*M*=0.71, *SD*=0.12) were solved more quickly than untrained problems (*M*=0.86, *SD*=0.17), *F*(1, 18) = 34.43, *p*=0.001, η^2=0.11. Trained problems were also solved more accurately (*M*=99.14, *SD*=1.49) than untrained problems (*M*=98.13, *SD*=1.93); *F(*1, 18) = 5.10, *p*=0.037, η^2=0.30.

4.5.3 Training x Strategy interaction

A significant interaction was found between Strategy and Training and their effects on RT, with *F*(1, 18) = 27.80, *p*=0.001. Figure 4.1 shows the nature of this interaction - essentially, the RT difference between memorized and calculated problems is much larger for untrained than for trained problems – in other words training impacts calculation RT much more than memory RT. In terms of accuracy, no significant interaction was found; *F*(1, 18) = 0.01, *n.s.*

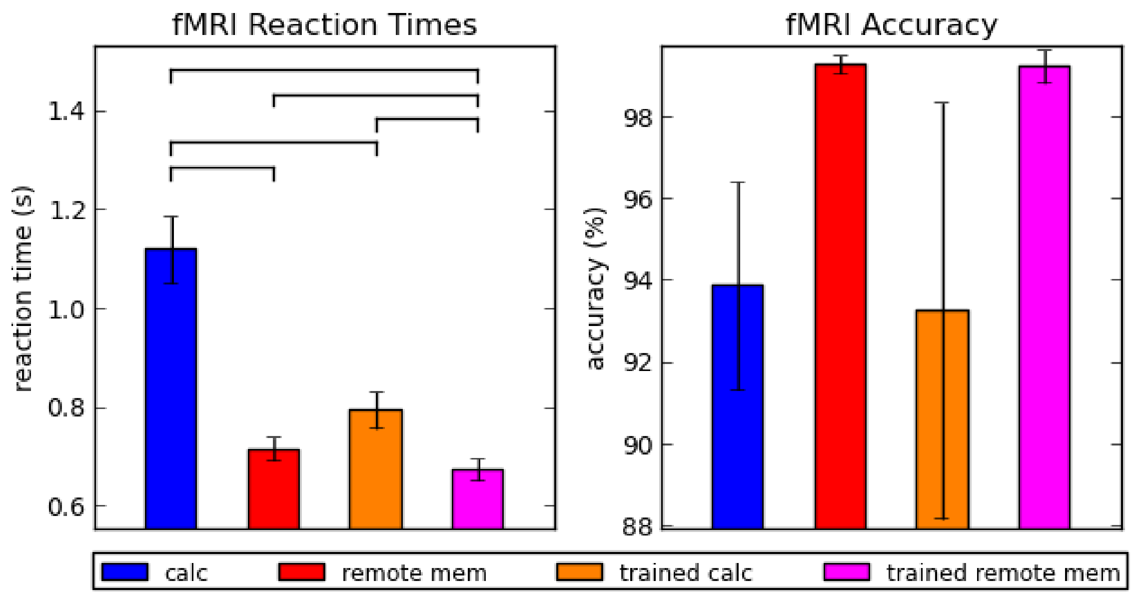

Figure 4.1: Bar charts showing accuracy and reaction time for fMRI task.

4.6 Results – Post training fMRI

4.6.1 Main effect of strategy

Memorized problems were contrasted against calculated problems (combining both trained and untrained problems). This contrast was similar to the memorized > calculated contrast in Chapter 3, but differed because it included both trained and untrained problems. The results, as expected, were very similar to those obtained in Chapter 3 (which only considered untrained calculation and untrained memorized problems). Bilateral AG and SMG were more active in memorized problems than they were in calculated problems, with the reverse contrast yielding widespread frontoparietal activation. However, unlike in the contrast of untrained memory > untrained calculation in Chapter 3, no differences in hippocampal activity were observed (though when the threshold was lowered, a cluster in that region did appear). Furthermore, a cluster in the left vmPFC (see Figure 4.2) was more active in the memorized condition, which was not observed in the previous Chapter.

The main effects of Training, Strategy, and the Interaction between them

Trained > Untrained

Left					Right				
	x	**y**	**z**	**extent**		**x**	**y**	**z**	**extent**
Angular Gyrus, Supramarginal Gyrus	-50	-54	24	1175	Angular Gyrus, Supramarginal Gyrus	52	-54	27	835
Mid Cingulate	-2	-17	32	1307					
Mid Temp	-59	-14	-12	1336	Mid Temp	50	-16	-5	3916
Putamen	-28	-9	8	958	Striatum	23	-10	11	544

Memorized > Calculated

Left					Right				
	x	**y**	**z**	**extent**		**x**	**y**	**z**	**extent**
Angular Gyrus	-49	-61	21	2962	Angular Gyrus, Supramarginal Gyrus	52	-54	26	1603
					Temporoparietal Junction	52	-29	22	773
Anterior Cingulate	-3	29	-7	1003					
vm Prefrontal Cortex	-22	39	-13	688					
Temp Pole	-41	14	-25	658					

Calculated > Memorized

Left					Right				
	X	**y**	**z**	**extent**		**x**	**y**	**z**	**extent**
IPS, SPL	-26	-60	43	40664	IPS, SPL	25	-57	44	39568
Anterior Cingulate Cortex	-6	12	43	17916	Anterior Cingulate Cortex	5	12	42	14368
					PCC	12	-64	14	1263
Mid Front	-38	13	26	46769	Mid Front	35	16	28	41140
Occipital	-34	-71	-10	50022	Occipital	28	-71	-11	49143
Thalamus, Striatum	-11	-9	3	21615	Thalamus, Striatum	9	-8	4	19245
Culmen, Declive	-7	-58	-12	11309					

Strategy x Training

Left					Right				
	x	**y**	**z**	**extent**		**x**	**y**	**z**	**extent**
Angular Gyrus, Supramarginal Gyrus	-50	-54	24	1257	Angular Gyrus, Supramarginal Gyrus	52	-54	27	904
Mid Temp	-58	-14	-12	1414	Mid Temp	50	-16	-5	4154
Putamen, Pallidum	-28	-9	8	1028	Putamen	24	-10	11	607
Mid Cingulate	-2	-17	32	1417					

Table 4.1: x, y, and z coordinates indicate center of cluster. Extent indicates volume in mm^3 of each cluster.

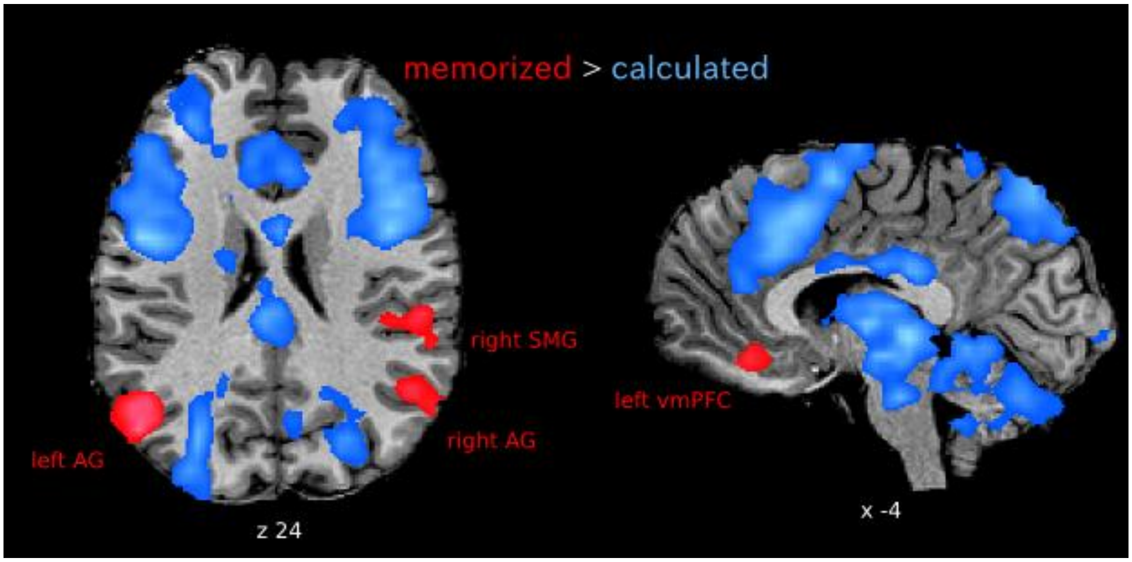

Figure 4.2: Regions of significant activity for the contrast of memorized > calculated problems.

4.6.1.1 Main effect of training

There was also significant main effect of training. When comparing trained > untrained problems, activity was observed in the bilateral AG/SMG, the bilateral middle temporal cortex, the ACC as well as the bilateral striatum (in particular, the putamen). The reverse contrast revealed no differences in activation. While the greater AG and ACC activation in the contrast of trained > untrained is consistent with previous research (Delazer et al., 2003, 2005; Grabner et al., 2009; Ischebeck et al., 2007), the fact that the contrast of untrained > trained yielded no differences in activation is atypical. This could be due to the fact that the strategies were balanced between the trained and untrained conditions, which is not normally the case in training studies (typically most problems in the training set are assumed to be memorized and most problems in the untrained set are assumed to be calculated, though this is never explicitly controlled for). Similarly, the training effect described in Chapter 3 came from a contrast which comprised of memorized problems in the trained condition, and all calculated problems in the untrained condition.

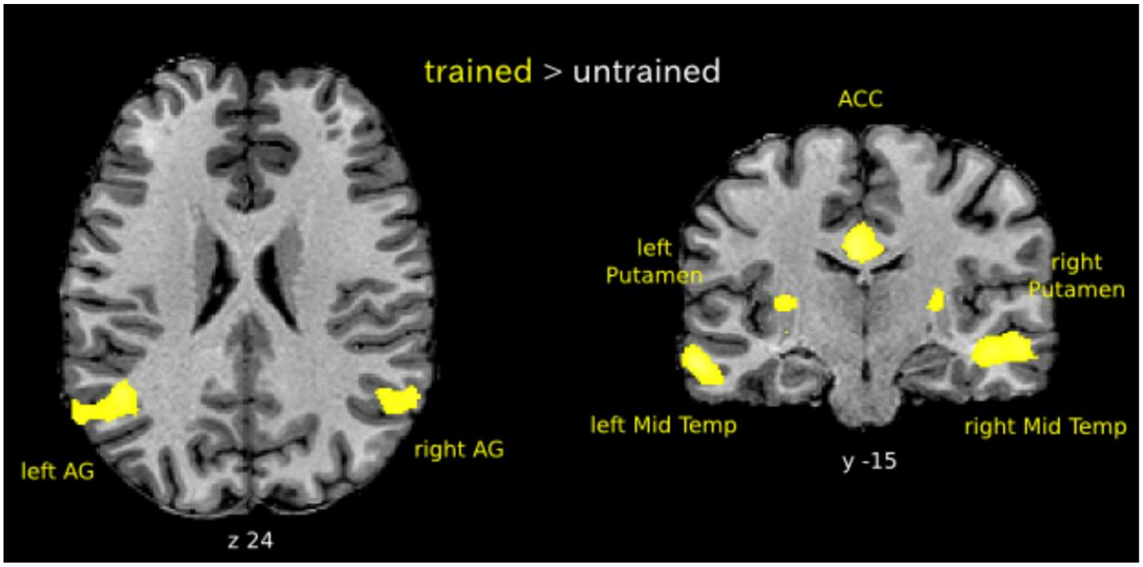

Figure 4.3: Regions of significant activity for the contrast of trained > untrained problems.

4.6.1.2 Training Effects – Training x Strategy interaction

The interaction of Training and Strategy was tested in the context of a whole-brain 2x2 ANOVA. Seven clusters of activity were found to be affected by the interaction of strategy in training, shown in Figures 5, 6 and 7. The co-ordinates of these clusters are listed in Table 4.1. To clarify the nature of the interaction occurring in each cluster, beta weights were extracted from the clusters obtained from the whole-brain 2x2 ANOVA and their main effects analyzed. These results are presented in Table 4.2.

Cluster	Strategy	Training
R Mid Temp	*t*(18.0)=0.14, n.s.	*t*(18.0)=-5.23, *p*=0.001
R SMG, Angular Gyrus	*t*(18.0)=-4.22, *p*=0.001	*t*(18.0)=-3.73, *p*=0.002
R Putamen	*t*(18.0)=2.55, *p*=0.020	*t*(18.0)=-4.11, *p*=0.001
Mid Cingulate	*t*(18.0)=3.71, *p*=0.002	*t*(18.0)=-4.83, *p*=0.001
L Putamen	*t*(18.0)=0.21, n.s.	*t*(18.0)=-3.87, *p*=0.001
L SMG, Angular Gyrus	*t*(18.0)=-5.12, *p*=0.001	*t*(18.0)=-4.39, *p*=0.001
L Mid Temp	*t*(18.0)=-1.33, n.s.	*t*(18.0)=-3.92, *p*=0.001

Table 4.2: Main effects of Strategy and Training on the beta weights for the clusters obtained from the Training x Strategy interaction.

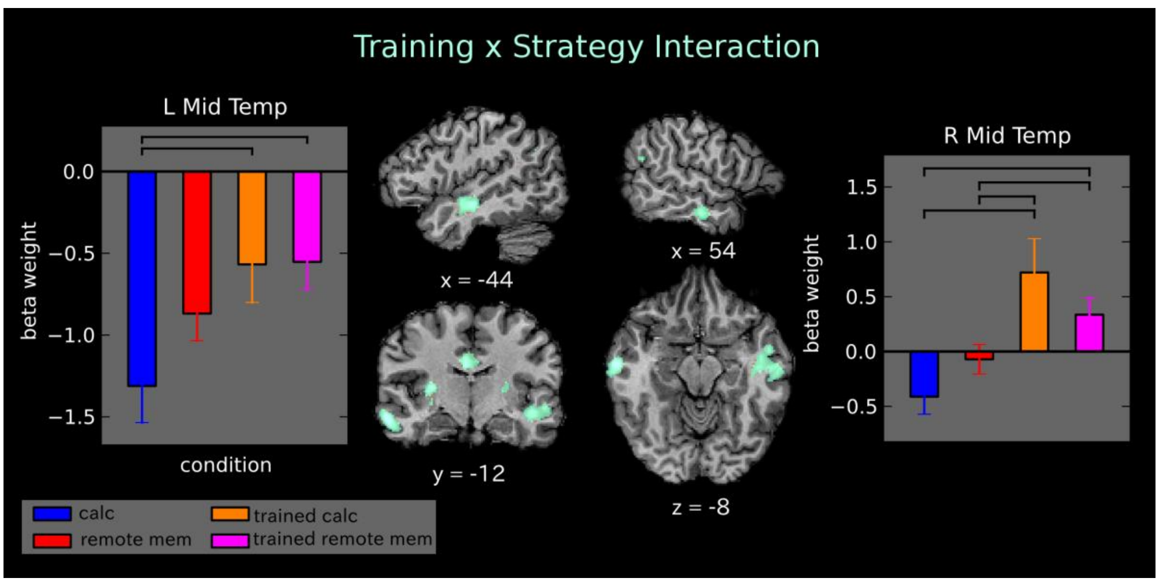

Figure 4.4: Brain regions showing significant interaction effects of Strategy and Training in the middle temporal gyri. Bar charts show beta weights for untrained calculated (blue), untrained memorized (red), trained calculated (orange), and trained memorized (pink) problems.

Figure 4.4 shows inter-hemispheric differences in the activity of the middle temporal clusters. A clear crossover interaction occurred in the right middle temporal gyrus, with the cluster being most active during the solving of trained calculated problems, followed by trained memorized problems. In the left middle temporal gyrus, trained problems also had higher beta weights than untrained problems, but the interaction in this cluster was due a lack of a difference between memorized and calculated problems in the trained condition.

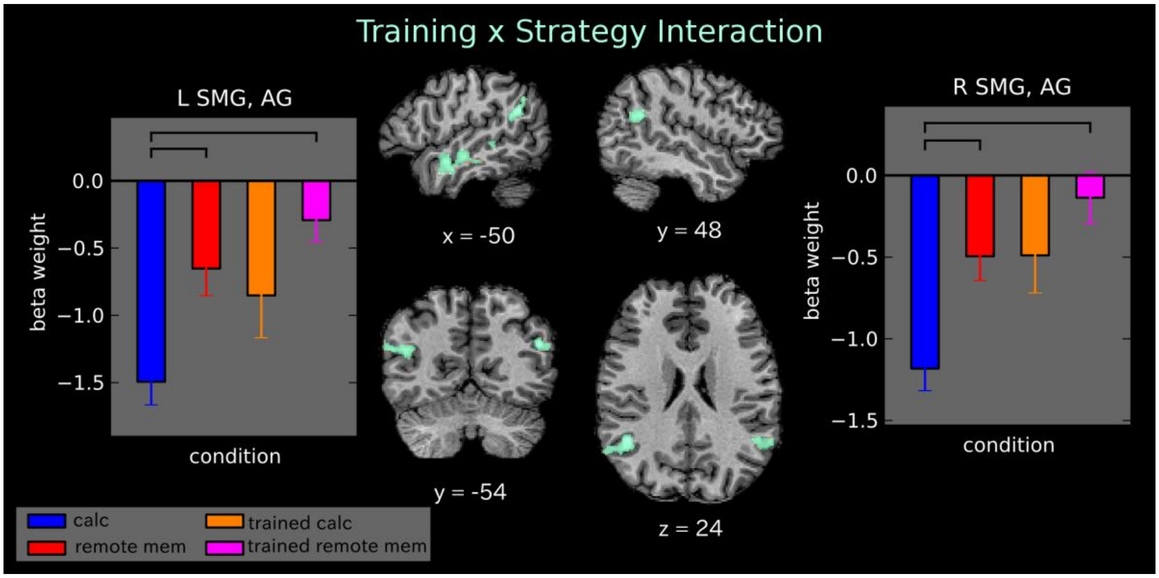

Figure 4.5: Brain regions showing significant interaction effects of Strategy and Training in the bilateral SMG and AG. Bar charts show beta weights for untrained calculated (blue), untrained memorized (red), trained calculated (orange), and trained memorized (pink) problems.

Figure 4.5 shows the beta weights for the clusters located in the left and right AG and SMG. It was predicted that the angular gyrus might show activation patterns indicating selectivity for retrieval problems, and this was observed. However, the trained problems showed less deactivation than the untrained problems, and the difference in beta weights between the memorized and calculated problems was not significant in the trained condition (see Table 4.2). In other words, training increased the beta weights of the calculated problems, such that they became similar to those of memorized problems.

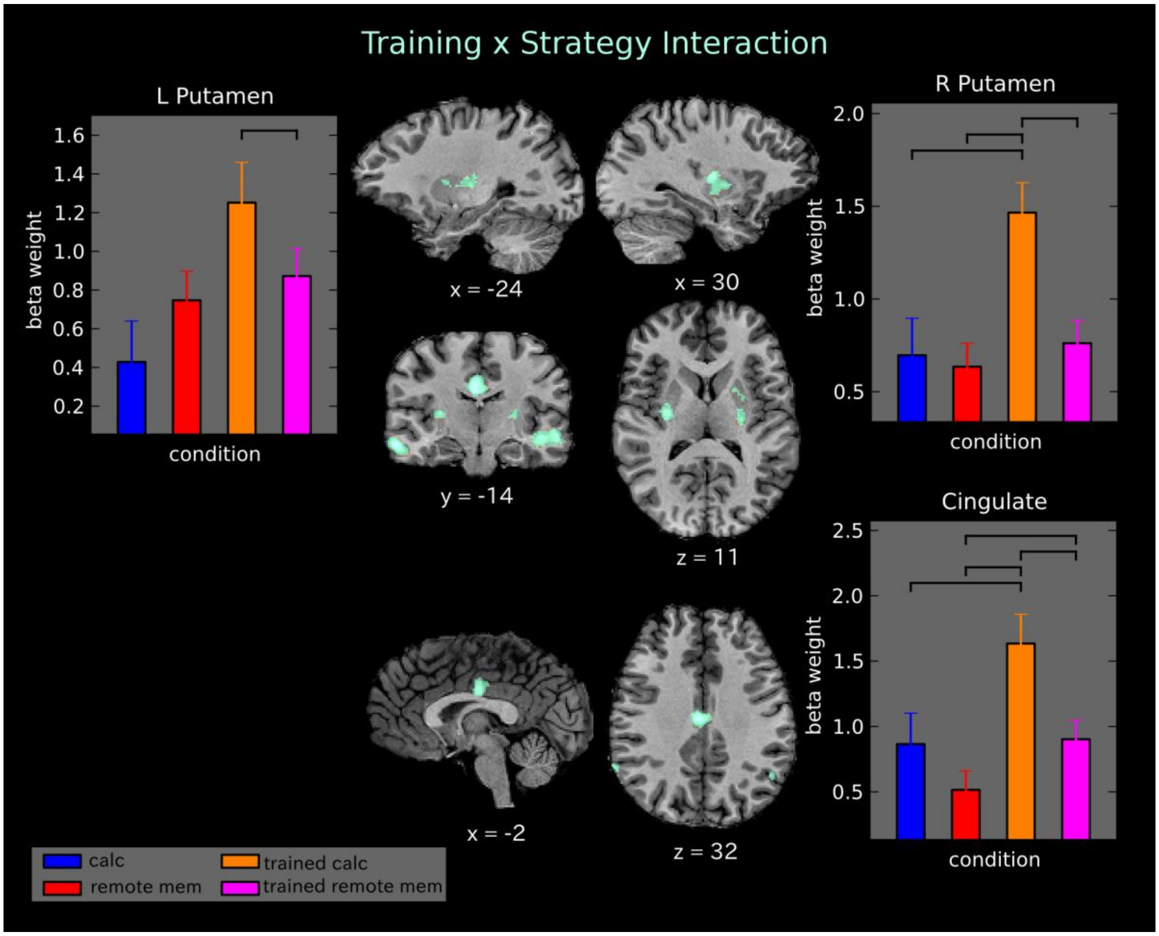

Figure 4.6: Brain regions showing significant interaction effects of Strategy and Training in the left and right putamen and mid cingulate. Bar charts show beta weights for untrained calculated (blue), untrained memorized (red), trained calculated (orange), and trained memorized (pink) problems.

Figure 4.6 shows an increased response for the trained calculated problems (orange bars) in both the left and right putamen and the mid cingulate cortex. In particular, the right putamen was preferentially activated for the trained calculated problems. One important caveat for this set of findings is that there were not many observations in the trained calculated condition because most of the calculated problems in the training sets became memorized post-training. To examine whether data from participants with low trial numbers biased the results, beta weights for trained and untrained calculation problems were extracted from the cluster in the right putamen and the difference scores (between trained and untrained calculated problems) computed for each participant. Then, these difference scores (e.g., the difference between untrained and trained calculation problems) were correlated with the number of trials available in the trained calculated condition (see Figure 4.7). No significant correlation was found, with $r(17) = -0.40$, n.s. However, this does not completely solve the issue of low trials, as the scores used in the correlation were also impacted by the low sample size. To be certain of an association between greater putamen activity and well rehearsed procedural calculation, this experiment must be replicated with a larger number of observations in the trained calculation condition.

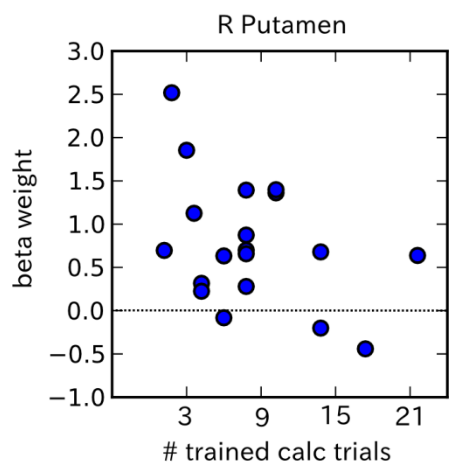

Figure 4.7: Scatter plot of the difference in beta weights between trained and untrained calculated problems vs. number of trained calculation trials (data from cluster in the right putamen).

4.7 Discussion

The goal of the current study was to examine how patterns of brain activity associated with fact retrieval and procedural calculation are modulated by training. Data obtained from the experiment described in Chapter 3 was used to examine this issue directly. Self-reports (either memorized or calculated) were obtained both before and after training. Only problems that were either memorized or calculated both before and after training were examined (unlike in Chapter 3 in which problems that were calculated, but became memorized were the focus of the analysis). This allowed for the analysis of both the main effects of strategy as well as their interactions.

The key analysis was the whole-brain test of the interaction of training and strategy. Before performing this interaction, the main effects of training and strategy first were measured. The main effect of strategy was found to be largely consistent with the results of Chapter 3's contrast of untrained memorized > untrained calculated problems, save for the greater hippocampal activation which was absent from this contrast. The main effect of training was different from that found in previous research, with no activity found in the untrained > trained contrast (which normally yields widespread activation). However, the trained > untrained contrast was similar, with greater activation in bilateral AG and the mid cingulate (as well as middle temporal gyri). Finally, the whole-brain interaction revealed seven regions which showed an interaction of strategy and training in their profile of activity. Notably, it was found that AG activity was increased even in the absence of a shift in strategy, and that striatal activity, particularly activity in the right putamen, was highest among the trained calculated problems.

4.7.1 Main effects of strategy and training

The main effect of strategy was, as predicted, similar to previous studies of arithmetic strategy (Grabner et al., 2009) as well as the results of Chapter 3. However, unlike in Chapter 3, no hippocampal activity was observed. Thus, the inclusion of trained problems in the contrast must have attenuated any differences between the memorized and calculated problems.

The main effect of training produced a very interesting result. While AG and mid cingulate activity was greater in the trained > untrained contrast, no differences in activity were found for the reverse contrast. This is not consistent with the results of previous training studies, which showed greater widespread frontoparietal activation in the trained relative to the untrained condition (Delazer et al., 2003, 2005; Grabner et al., 2009; Ischebeck et al., 2007). This was likely due to the fact that strategy use was balanced in this study. Simply put, the trained and untrained problems were roughly equivalent in terms of the number of problems solved by calculation and by fact retrieval, whereas in previous work most studies were designed such that trained problems were solved by fact retrieval, and most untrained problems through calculation (though this can't be known with certainty because strategy was not tracked). The current result challenges one of the main assumptions regarding the effects of arithmetic training, which states that training leads to a shift from widespread to focal activity (Zamarian, Ischebeck, & Delazer, 2009). The present data suggest that this assumption only applies in cases where a shift in strategy also takes place. When training does not result in a strategy shift, only an increase in activation for the trained problems was seen, specifically in the AG, middle temporal gyrus (e.g., BA 21), mid cingulate gyrus, and putamen. Untrained problems, by comparison, were not associated with activity in any regions that were not already active for the trained problems. Thus, in the absence of a shift in strategy, no focalization of activity appears to take place due to training. Rather, activity in key regions is amplified. This change in activity should be described as a domain-general effect, as increases are seen for both strategies. This is consistent with arithmetic training research that examined training effects on both an arithmetic and a figural-spatial task, and found greater AG activity for the trained > untrained on both tasks (Grabner et al., 2009).

4.7.2 Interactions

Interestingly, the clusters (e.g., AG, Mid Temp, Cingulate and putamen) revealed by the Training x Strategy interaction were in the same regions as those revealed by the contrast of Trained > Untrained problems. Among these clusters, 3 types of interaction were observed. The first was a crossover interaction which occurred in right middle temporal gyrus, with this cluster being most active during the solving of trained calculated problems, followed by trained memorized problems. The second type was a dampening (by training) of the strategy difference – in other words, the difference between calculated and memorized problems was smaller in the trained than the untrained condition. This occurred in the bilateral AG, and the left middle temporal gyrus. Finally, the last type of interaction was due higher activity in one condition only (trained calculation), which occurred in the putamen and the mid cingulate.

4.7.2.1 Interactions in the angular gyrus

The AG is described by the triple-code model and its extension as being associated with fact retrieval (Arsalidou & Taylor, 2011; Dehaene et al., 2003). Specifically, it is associated with symbol-referent mapping (Ansari, 2008), where a mapping is made between a particular arithmetic equation and its solution. This notion is supported by the findings of Chapter 3, which showed that AG activity was greater among problems solved by fact retrieval, regardless of when they became memorized. However, the current analysis showed that untrained calculated problems had lower AG activation than trained calculated problems - thus training was associated with an increase in angular gyrus activity even when the same strategy was used. One interpretation for this is that the strength of the mapping between the problem and the solution is reflected in greater AG activation. The stronger the mapping, the more likely it is that the problem can be solved via fact retrieval. This would imply that the trained calculated problems are on the cusp of being memorized, as the AG activation for trained calculated and untrained memorized problems is about even. Consistent with this notion, the highest activation was found among the trained memorized problems, suggesting a very strong mapping between the problem (the symbol) and its solution (the referent).

An alternative interpretation for this data relates to the ease at which these operations are performed. Activity in the AG has been associated with automatic retrieval processes – in other words, items that are automatically retrieved from memory are associated with higher AG activity. Items that require a more directed search to be retrieved, by contrast, are associated with activity in the IPS (Hutchinson & Turk-Browne, 2012). This is quite consistent with the trained/untrained difference found among the memorized problems (a trained retrieval is performed more easily than an untrained one), but less so among the calculated problems. However it is possible that, among calculated problems, this higher AG activity is related to the ease at which the appropriate heuristic is retrieved, or perhaps the retrieval of intermediate solutions (e.g., transformation of the digits in the problems). In other words, with practice, the intermediate retrieval operations become more automatic, resulting in increased AG activity. If this is the case, the definition of a ‘referent’ in the context of a symbol-referent mapping (Ansari, 2008) could be expanded to include a particular problem-solving algorithm/heuristic.

4.7.2.2 Interactions in the putamen

The idea that a particular algorithm/heuristic may be mapped to a given equation is supported by the finding that striatal structures, particularly the putamen, are highly active for trained calculated problems (which, importantly, were solved significantly faster than untrained calculated problems). Activity in these regions is associated with procedural/implicit learning (Saint-Cyr, Taylor, & Lang, 1988), and it may be the case that training an arithmetic problem results in the heuristic used to solve that problem becoming automated (yet still, upon introspection, identified as calculated). This effect was specific to calculation, so it is likely that it is the heuristic that is being automated or strengthened (rather than fact retrieval as is thought to be the case in the AG). It has previously been speculated from lesion studies that the basal ganglia may provide the anatomical basis for procedural arithmetic knowledge (Roşca, 2009), and the results present in this study provide the first functional evidence that is supportive of this claim. This raises some interesting questions with regards to how this increased putamen activity should be interpreted. For instance, given a protracted training schedule, would these problems eventually be solved through fact retrieval? Or, would these problems continue to be solved through efficient calculation strategies?

Lastly, two clusters were observed in the middle temporal gyrus. These areas are not implicated with arithmetic performance by either the triple-code model or its recommended updates, as they lie outside the perisylvian cortex (in BA 21). The fact that the cross-over interaction occurs on the right and not the left cluster is suggestive that this activation is related to language in some way, but the precise nature of this association is unclear.

4.7.3 Limitations and future directions

Though the increased activity in the putamen during the solving of trained calculation problems is very interesting, this was not predicted by any previous research. As such, replication is of the utmost importance. Furthermore, because participants successfully memorized the majority of problems in their training sets, for some participants there were a low number of trained calculation trials present. It was demonstrated in Chapter 2 that by adding more problems to the training set (and reducing the duration of the training period) would decrease memorization rates, increasing the amount of trained calculated problems in the set. Thus, this experiment could be repeated with a larger training set in order to provide more trained calculation problems for analysis.

Another potential limitation with this procedure lies in the use of self-reports. Though in Chapter 2 it was established that the self-report measures are reliable and valid, the possibility exists that the trained calculated problems are in fact memorized, and being misreported as calculated. However, while the AG activation indicates some similarity between trained calculated problems and memorized problems, the higher activation in the putamen and mid cingulate suggests that they are indeed different. Furthermore, the general consensus in the literature states that it is in fact well rehearsed calculation that is often misreported as fact retrieval (Baroody, 1983; Fayol & Thevenot, 2012), which is in fact the reverse problem. Thus, it is unlikely that the misreporting of strategy is at play here.

4.7.4 Conclusion

Two main conclusions can be drawn from this data. First, it provides important context to the training effects described in Chapter 3. Notably, angular gyrus activity increases with training, even in the absence of a shift in strategy, perhaps reflecting an ongoing strengthening of the mapping between problem and solution. Thus, training-induced increases in activity in the AG (as well as the putamen, middle temporal, and mid cingulate gyrus) will occur even in the absence of a shift in strategy. Furthermore, while previous research has consistently obtained widespread frontoparietal activity among the untrained as opposed to the trained problems, no such difference in activation was found in this data set. Thus, while AG activity resulting from training is not dependent on differences in strategy, the greater widespread activation associated with the solving of untrained problems is. Finally, the finding that activity in the putamen was selectively higher during the solving of trained calculation problems suggests a role for the procedural memory system in arithmetic problem solving, particularly the act of calculation.

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Chapter 5

5 Conclusion

Given that proficiency with mathematics is linked to many positive life outcomes, it follows that boosting mathematical abilities among the general population has potential benefits to society. Understanding the neural correlates of mental arithmetic may one day be able to inform more effective educational programs - however, despite a large amount of work regarding the neural correlates of arithmetic learning, current models of number processing treat the network of brain regions that underlie arithmetic skill as a static system. The experiments presented in this dissertation, conducted using the Customized Arithmetic Training (CAT) protocol, demonstrate that practicing mental arithmetic induces changes in brain activation, and that the extent and distribution of this activation varies depending on whether it is procedural calculation or fact retrieval that is being rehearsed. These changes can result from a shift in strategy use, but also from the rehearsal of the fact retrieval or calculation process.

Chapter 2 described the development of the CAT protocol using a pair of behavioral experiments. Using self-report information, uniquely tailored problem sets were created for each participant, which were then used in a five-day web-based arithmetic training program. Strategy use in each set was balanced such that participants solved half the problems by retrieving the solution from memory and the other half were solved through procedural calculation. Memorized problems were found to have smaller pre-training sums than calculated problems and were also solved more quickly than calculated problems, indicating that the self-reports were valid. Strategy use remained consistent both within and between tasks (as assessed by % of problems being solved by the same strategy), with the two tasks being a voice production task and an arithmetic choice task. Learning rates (e.g., how many calculated problems would become memorized following training) were measured, and it was found that many of the calculated problems were reported as memorized following training. Having established the reliability and face validity of the self-report measures using the voice and choice task, another experiment was conducted using only the arithmetic choice task because it was more suitable for fMRI experimentation. It was concluded from these two experiments that the CAT protocol provided a viable means to control for strategy use between participants in the context of an arithmetic training program, which was a crucial step in this series of experiments given the novelty of the paradigm. This protocol was then used to study arithmetic training effects in a neuroimaging experiment, the results of which are described in Chapters 3 and 4.

In Chapter 3, the neural correlates of arithmetic fact retrieval were examined. The CAT protocol developed in Chapter 2 was used to generate individually tailored problems for each participant such that half the problems were solved through fact retrieval and the other half were solved through calculation. After obtaining these sets, a subset of these problems was then rehearsed by participants over a six-day period through a web-based training program. Following training, participants underwent an fMRI session in which they solved both the trained and the untrained problems. After the scan they were presented with all the problems again and provided a self-report indicating what strategy they used to solve each problem. This allowed for the labeling of problems as either calculated, memorized, or recently memorized. The neural correlates of fact retrieval were first examined by comparing untrained calculated and untrained memorized problems. Results were consistent with previous research, with greater angular gyrus (AG) activity for memorized problems (Grabner, Ansari, et al., 2009). However, in contrast to previous studies, activity in the right anterior hippocampus was also observed to be greater for memorized compared to calculated problems. Second, training effects relating to memorization were analyzed by comparing recently memorized problems against calculated problems. Widespread frontoparietal activity was greater during procedural calculation, whereas during the retrieval of recently memorized facts (e.g., calculated problems whose solutions became memorized through training) more activity in the bilateral angular gyri and anterior cingulate was observed. Finally, evidence of a temporal gradient during fact retrieval was found by comparing recently memorized facts against those that had been known since before the study began, indicating that recently learned memories were not as deeply encoded as older memories. Notably, activation was greater in the intraparietal sulcus (IPS), anterior cingulate, and frontal regions during the retrieval of recent versus remote arithmetic facts. From the above findings it was concluded that much of what has been reported as a training effect in the existing literature is likely driven by changes in the balance of strategy that participants are using pre and post training. However, to date it was unknown to what extent training could modulate brain activity in the absence of a shift in strategy.

In Chapter 4, strategy-specific training effects were examined. In other words, only problems that were either memorized or calculated both before and after training were studied (whereas the focus in Chapter 3 was on problems that were calculated, but became memorized). This allowed for the analysis of both the main effects of strategy as well as their interactions. Regions of the brain that were differentially modulated by training (depending on strategy) were isolated by conducting a whole-brain test of the interaction between strategy and training. The main effect of training was found to be largely consistent with the results of Chapter 3's contrast of untrained memorized > untrained calculated problems, save for the greater hippocampal activation which was absent from this contrast. The main effect of training was different from that found in previous research, with no activity found in the untrained > trained contrast (which normally yields widespread activation). However, the trained > untrained contrast was similar to previous work, with greater activation in bilateral AG and the mid cingulate (Delazer et al., 2003; Grabner, Ischebeck, et al., 2009; Ischebeck et al., 2006). Finally, the whole-brain interaction revealed seven clusters of activation. Notably, it was found that AG activity was modulated by training even in the absence of a shift in strategy, and that striatal activity, particularly activity in the right putamen, was highest among the trained calculated problems. The AG activity appeared to be a general training effect, given that increases in AG activity were seen even when strategies remained the same. The activity in the putamen was also interesting, as it suggested association between the procedural memory system and mental arithmetic.

These studies implicate brain structures not previously associated with mental arithmetic, namely the putamen and the anterior hippocampus. They also provide support for common assumptions underlying previous arithmetic training research – namely that training effects observed to date may reflect a shift from a calculation to a memory-based problem solving strategy. However, this is not the sole source of training effects. In the absence of a shift in strategy, an increase in activation in task-relevant regions was observed. Much of the training literature contains references to the notion that training induces a shift from widespread to focal activation of task-relevant regions, and this viewpoint is pervasive enough that it is repeated in reviews of arithmetic training literature (Zamarian, Ischebeck, & Delazer, 2009). However, when strategy does not change, training does not have this effect – it simply brings about an increase in activation in task-relevant regions, and no decrease in activation elsewhere. Taken together, these patterns of results provide valuable insights into the neural substrates of fact retrieval and procedural calculation. Furthermore, they highlight the important of using individualized sets of problems in the study of the neural correlates of mental arithmetic.

5.1 Fact Retrieval

Three structures in particular were found to be associated with fact retrieval and are worth discussing; the medial temporal lobe (MTL), the angular gyrus and the IPS. First, the MTL has been shown to be necessary for the binding of items together in contexts (Cohen & Eichenbaum, 1993; Cohen, Poldrack, & Eichenbaum, 1997; Eichenbaum & Cohen, 2001), which is a key aspect of episodic memory. Viewed from a relational perspective, each arithmetic fact is a set of items (numbers) that are bound together in a given context (the operation being performed). This is not to say that 2+2=4 is an episodic memory. Rather, that episodic memories and memories of arithmetic facts may share a common feature (binding), which is also associated with MTL activity. Interestingly however, MTL activity during retrieval of arithmetic facts appeared to be temporally graded, with older memories associated with more hippocampal activity than newer memories.

In contrast, activation of the angular gyrus did not appear temporally graded, and it was found to be more active in both old and new memories (as compared to problems solved by calculation). The AG is described by the triple-code model and its extension as being associated with fact retrieval (Arsalidou & Taylor, 2011; Dehaene, Piazza, Pinel, & Cohen, 2003). Specifically, it is associated with symbol-referent mapping (Ansari, 2008) where a mapping is made between a particular arithmetic equation and its solution. This notion is supported by the findings of Chapter 3, which showed that AG activity was greater among problems solved by fact retrieval, regardless of when they became memorized. However, Chapter 4 showed that untrained calculated problems had lower AG activation than trained calculated problems - thus training was associated with an increase in angular gyrus activity even when the same strategy was used. This increase may correspond with a strengthening of the link between problem and solution. It is possible then that this higher AG activity indicates that these trained calculated problems are on the verge of being memorized. In any case, the present data suggest that AG activity may not have a specific role in terms of fact retrieval given that strong training effects were seen in Chapter 4 even when the data was collapsed across strategies.

Lastly, activity in the IPS was also detected in the recently memorized problems (as well as calculated problems). Reflexive retrieval of an arithmetic fact is typically associated with AG, not IPS activity. However, when recently memorized problems were compared to problems that were solved by memory since before the study began, it was observed that the bilateral IPS was more active during the retrieval of recently memorized facts. IPS activity, though typically associated with calculation, may still be playing a role in retrieval – specifically, goal-directed search (Hutchinson & Turk-Browne, 2012). When a person uses procedural calculation to solve a problem such as 15 + 24, they first determine which intermediate facts to retrieve from memory – e.g., the answers to 5 + 4 and 1 + 2. In this way, IPS activity may be associated with the search for and/or retrieval of the intermediate arithmetic facts. Why, then, the increased IPS activity for recently memorized problems as compared to memorized problems that have been known for long periods of time? One possibility is that the six-day training program is insufficient to commit these facts to memory such that they are effortlessly retrieved (e.g., the solution comes to mind upon being presented with the problem). Specifically, the factor that cues the participant to engage in retrieval may be different. While remote memory problems are retrieved automatically, recently memorized facts may be recognized them as familiar, and this feeling of familiarity prompts a memory search. In this way, a retrieval strategy is used to solve the recent memory problems, but the act of retrieval is still more effortful than for a problem where the solution automatically comes to mind.

5.2 Calculation

Results of Chapter 4 suggested, as have the results of some lesion studies (Roşca, 2009), that there is an association between the basal ganglia and procedural calculation. The idea that a particular algorithm/heuristic may be mapped to a given equation is supported by the finding that striatal structures, particularly the putamen, are highly active for trained calculated problems (which, importantly, were solved significantly faster than untrained calculated problems). Activity in these regions is correlated with procedural/implicit learning (Saint-Cyr, Taylor, & Lang, 1988), and it may be the case that training an arithmetic problem results in the heuristic used to solve that problem becoming automated (yet still, upon introspection, identified as calculated). This effect was specific to calculation, so it is likely that it is the heuristic that is being automated or strengthened (rather than a mapping between problem and solution as is thought to be the case in the AG). It has previously been speculated from lesion studies that the basal ganglia may provide the anatomical basis for procedural arithmetic knowledge (Roşca, 2009), and the results present in this study provide the first functional evidence for this claim. This raises some interesting questions with regards to how this greater putamen activity should be interpreted. For instance, given a protracted training schedule, would these problems eventually be solved through fact retrieval? Or, would these problems continue to be solved through efficient calculation strategies?

5.3 Future Directions

5.3.1 Developmental differences

The most promising application of the CAT paradigm is to study developmental populations. Activity in the parietal cortex is positively correlated with age, whereas activity in the prefrontal cortex and medial temporal lobe is correlated negatively with age (Rivera, Reiss, Eckert, & Menon, 2005). This result has led to the widespread assumption that hippocampal activity during mental arithmetic is unique to children. In children, increased hippocampal activation has been shown when comparing children who either relied mostly on retrieval or mostly on more effortful calculation (Cho et al., 2012; Cho, Ryali, Geary, & Menon, 2011). MVPA was used to classify children who relied mainly on memory or on counting to solve arithmetic problems. This revealed differences in the spatial pattern of activity in the hippocampus and the parahippocampal cortex (PHC), but not in the extent of activation. In the 2012 study, which used a stricter criterion for determining whether a child was a 'retriever' (e.g., they had to rely on retrieval a greater proportion of the time), activation differences in the hippocampus and PHC were found.

While the data above are suggestive of a developmental difference between children and adults, findings from Chapter 3 indicate that the hippocampus is indeed active during fact retrieval in adults. Furthermore, some of the developmental differences observed by Rivera et al. (2005) may be attributable to differences in strategy use, with younger children relying mainly on procedural strategies such as finger counting, and adults relying more on fact retrieval. By using the CAT paradigm on a group of children and adults, these differences in strategy use can be controlled for, allowing for a more precise characterization of developmental differences in the neural correlates of mental arithmetic. Specifically, it can be determined whether the developmental differences to date are simply the result of differences in strategy use, or whether other maturational factors are at play (more than likely there is a combination of both factors). Furthermore, it would be of great interest to assess whether the effects of training vary with chronological age.

5.3.2 Dynamic systems

Learning is a dynamic process, but existing models of mental arithmetic treat the neural substrates involved as a static system. Two lines of research can be extended to provide commentary on the dynamic nature of these systems. Firstly, CAT could be used to observe short-term changes in brain activity, such as those produced from a single in-scanner training session. Secondly, CAT could be used to explore how familiarity and recognition affects brain activity during the retrieval of arithmetic facts.

Practice effects are observable even within the context of a single fMRI session. By the end of a 28-minute session, activity in the bilateral AG and left middle temporal gyrus was shown to be higher for problems that are repeated than for untrained problems

(Ischebeck, Zamarian, Egger, Schocke, & Delazer, 2007). The CAT system could be used in a similar experiment, such that strategy is tracked before and after the session. In such a design, a set of memorized and calculated problems could be obtained before the fMRI session, and these would be subdivided such that half the problems would be repeated throughout the scan, and half the problems would be shown only once. It is likely that among the repeated problems, many of the calculated problems would become memorized – essentially allowing for the observation of a shift from calculation to fact retrieval as it happens. From the results of Chapters 3 and 4, the level of activity in the AG in hippocampus seems to be indicative of the strength of the mapping between problem and solution. If this is the case, it may even be possible to predict whether problems would or not be reported as memorized based on fMRI data.

Strategy selection, e.g., determining whether to use a calculation or memory strategy depends party on the participant's ability to recognize the problem as either known or unknown. It has been proposed that recognition judgments are supported by two memory signals (Yonelinas, 2002). The first of these signals supports judgments that are accompanied by the recollection of qualitative information about a prior episode, such as remembering a particular problem from training. The second signal supports judgments that are based on a sense of familiarity without a link to a particular context. Interestingly, these signals can be found in regions associated with arithmetic fact retrieval; AG activity is associated with recollection, whereas IPS activity is modulated by familiarity (Johnson, Suzuki, & Rugg, 2013). This is particularly important because it may help explain the IPS activity during retrieval of recently learned facts, as was observed in Chapter 3. Thus, collecting familiarity information – i.e., determining whether or not a participant remembers a given problem from training or any other context, and their confidence in that memory, can be collected to assess the degree to which these signals influence overall brain activity during fact retrieval.

5.3.3 Structural correlates of arithmetic learning

While the present data concerned functional changes induced by training, the structural correlates of arithmetic learning can also be examined. Anatomical MRI and diffusion tensor images (DTI) were also collected during the experiment described in Chapters 3 and 4, and these will be examined to determine whether any brain structures correlate with learning rates observed during the CAT procedure. Of specific interest are the potential relations between learning rates and white matter tract thickness and grey matter density. It is known that math scores on the Preliminary Scholastic Aptitude test are positively correlated with fractional anisotropy (a measure of white matter tract integrity) in the left parietal cortex (Matejko, Price, Mazzocco, & Ansari, 2012). Thus it is quite plausible that similar relationships can be found between rates of memorization obtained using the CAT protocol and anatomical measures such as cortical thickness and white matter integrity.

An additional source of data not discussed in this thesis, but worthy of analysis, is the data obtained from the web-based training program itself. Reaction time and accuracy were collected for each trial, and thus it is possible to determine, for any given problem, at which point in the training process did significant changes in problem solving time occur. This information can then be used in concert with the fMRI data – for instance, would a problem which showed a significant RT decrease early in training have an activation profile that was different from a problem that showed a significant RT decrease later in training? Furthermore, would the time at which performance improved have any bearing on whether or not a problem would be reported as memorized post-training?

Finally, testing other operations and other strategies (Rosenberg-Lee, Lovett, & Anderson, 2009) would provide useful information. It is sometimes claimed that different arithmetic operations (such as addition vs. subtraction) have different neural underpinnings (Kong et al., 2005), however many of these differences may in fact be attributable to differential usage of fact retrieval and procedural calculation. By tracking strategy use, it can be determined whether the retrieval of a subtraction fact is the same as the retrieval of an addition fact. Similarly, differences in procedural calculation between different operations can be directly compared.

5.4 Summary

This series of experiments has clearly demonstrated that the brain systems necessary for performing mental arithmetic are both widespread and dynamic. Previous models of numerical cognition, namely the triple-code model and its recommended extensions, link arithmetic skill to the semantic memory system. However, results of this investigation suggest that some aspects of arithmetic skill also draw on aspects of the episodic and procedural memory systems. Though further research is warranted, a critical point made in this dissertation is that mental arithmetic is very much a distributed process, and its neural correlates are heavily influenced by factors such as strategy and practice.

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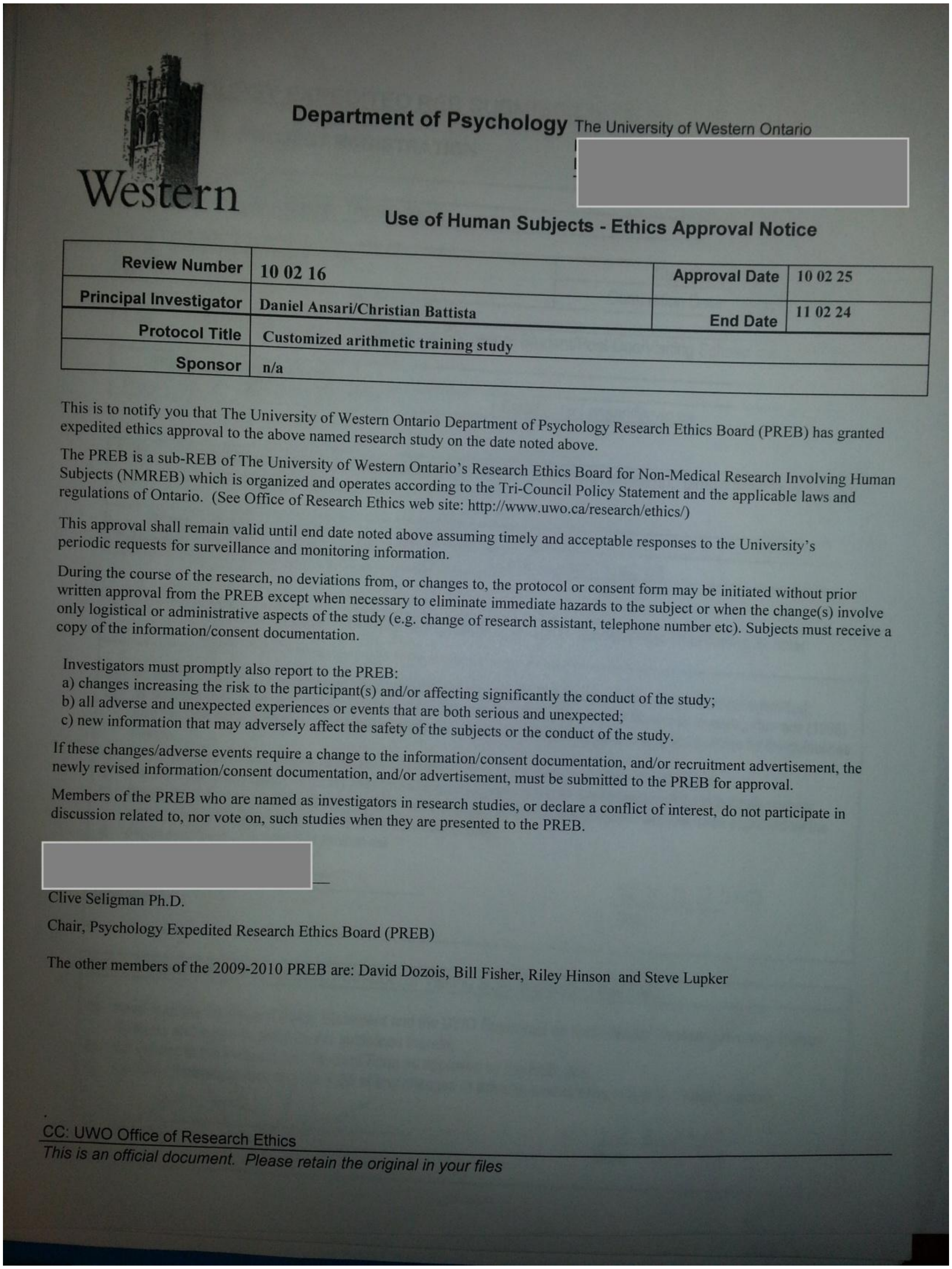
Appendices



Western

Department of Psychology The University of Western Ontario
[redacted]

Use of Human Subjects - Ethics Approval Notice

Review Number	10 02 16	**Approval Date**	10 02 25
Principal Investigator	Daniel Ansari/Christian Battista	**End Date**	11 02 24
Protocol Title	Customized arithmetic training study		
Sponsor	n/a		

This is to notify you that The University of Western Ontario Department of Psychology Research Ethics Board (PREB) has granted expedited ethics approval to the above named research study on the date noted above.

The PREB is a sub-REB of The University of Western Ontario's Research Ethics Board for Non-Medical Research Involving Human Subjects (NMREB) which is organized and operates according to the Tri-Council Policy Statement and the applicable laws and regulations of Ontario. (See Office of Research Ethics web site: http://www.uwo.ca/research/ethics/)

This approval shall remain valid until end date noted above assuming timely and acceptable responses to the University's periodic requests for surveillance and monitoring information.

During the course of the research, no deviations from, or changes to, the protocol or consent form may be initiated without prior written approval from the PREB except when necessary to eliminate immediate hazards to the subject or when the change(s) involve only logistical or administrative aspects of the study (e.g. change of research assistant, telephone number etc). Subjects must receive a copy of the information/consent documentation.

Investigators must promptly also report to the PREB:
a) changes increasing the risk to the participant(s) and/or affecting significantly the conduct of the study;
b) all adverse and unexpected experiences or events that are both serious and unexpected;
c) new information that may adversely affect the safety of the subjects or the conduct of the study.

If these changes/adverse events require a change to the information/consent documentation, and/or recruitment advertisement, the newly revised information/consent documentation, and/or advertisement, must be submitted to the PREB for approval.

Members of the PREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussion related to, nor vote on, such studies when they are presented to the PREB.

[redacted]
Clive Seligman Ph.D.

Chair, Psychology Expedited Research Ethics Board (PREB)

The other members of the 2009-2010 PREB are: David Dozois, Bill Fisher, Riley Hinson and Steve Lupker

CC: UWO Office of Research Ethics
This is an official document. Please retain the original in your files

Appendix A: Documentation of ethics approval for Chapter 2 experiments

Western Research

Research Ethics

Use of Human Participants - Ethics Approval Notice

Principal Investigator: Prof. Daniel Ansari
File Number:7281
Review Level: Delegated
Approved Local Adult Participants:48
Approved Local Minor Participants:*0*
Protocol Title: Neural correlates of arithmetic learning in children and adults
Department & Institution: Social Science\Psychology,Western University
Sponsor: Academic Development Fund UWO

Ethics Approval Date: August 30, 2012 **Expiry Date:**August 31, 2013
Documents Reviewed & Approved & Documents Received for Information:

Document Name	Comments	Version Date
Revised Study End Date	The study end date has been extended to August 31, 2013 to allow for continuation of data collection.	

This is to notify you that The University of Western Ontario Research Ethics Board for Health Sciences Research Involving Human Subjects (HSREB) which is organized and operates according to the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans and the Health Canada/ICH Good Clinical Practice Practices: Consolidated Guidelines; and the applicable laws and regulations of Ontario has reviewed and granted approval to the above referenced revision(s) or amendment(s) on the approval date noted above. The membership of this REB also complies with the membership requirements for REB's as defined in Division 5 of the Food and Drug Regulations.

The ethics approval for this study shall remain valid until the expiry date noted above assuming timely and acceptable responses to the HSREB's periodic requests for surveillance and monitoring information. If you require an updated approval notice prior to that time you must request it using the University of Western Ontario Updated Approval Request Form.

Members of the HSREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussion related to, nor vote on, such studies when they are presented to the HSREB.

The Chair of the HSREB is Dr. Joseph Gilbert. The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Signat

Ethics Officer to Contact for Further Information

X Janice Sutherland	Grace Kelly	Shantel Walcott

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Western University

Appendix B: Documentation of ethics approval for Chapter 3 and 4 experiments

Curriculum Vitae

Name:	Christian Battista
Post-secondary Education and Degrees:	University of Guelph Guelph, Ontario, Canada 2000-2005 B.Sc.
	University of Guelph Guelph, Ontario, Canada 2007-2009 M.A.
	The University of Western Ontario London, Ontario, Canada Ph.D. Candidate in Neuroscience 2009-Present
Honours and Awards:	Province of Ontario Graduate Scholarship [Declined] 2011
	Natural Sciences and Engineering Research Council (NSERC) Doctoral Fellowship 2011-2013
Related Work Experience	Teaching Assistant The University of Guelph 2007-2009
	Teaching Assistant The University of Western Ontario 2009-2011

Publications:

Holloway, I.D., Vogel, S. E., Battista, C. & Ansari, D. (in press) Semantic and perceptual processing of number symbols: evidence from a cross-linguistic fMRI adaptation study Journal of Cognitive Neuroscience.

Price, G. R., Palmer, D., Battista, C., & Ansari, D. (2012). Nonsymbolic numerical magnitude comparison: Reliability and validity of different task variants and outcome measures, and their relationship to arithmetic achievement in adults. Acta Psychologica, 140(1), 50–57. doi:10.1016/j.actpsy.2012.02.008

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