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Research report

The neural substrate of arithmetic operations and procedure complexity

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Abstract

Recent functional neuroimaging studies have begun to clarify how the human brain performs the everyday activities that require mental calculation. We used fMRI to test the hypotheses that there are specific neural networks dedicated to performing an arithmetic operation (e.g. + or −) and to performing processes that support more complex calculations. We found that the right inferior parietal lobule, left precuneus and left superior parietal gyrus are relatively specific for performing subtraction; and bilateral medial frontal/cingulate cortex are relatively specific for supporting arithmetic procedure complexity. We also found that greater difficulty level was associated with activation in a brain network including left inferior intraparietal sulcus, left inferior frontal gyrus and bilateral cingulate. Our results suggest that the network activated by the simplest calculation serves as a common basis, to which more regions are recruited for more difficult problems or different arithmetic operations.

Theme: Neural basis of behavior
Topic: Cognition

Keywords: Mental arithmetic; Calculation; fMRI; Brain network

1. Introduction

How the human brain encodes and manipulates information is a central issue in cognitive neuroscience. Mental calculation, which embodies logical thought and consequently represents an important component of higher order cognition, provides a good model to investigate fundamental cognitive processes. Over the last several decades, research and theory about cognitive processes that deal with numbers and arithmetic, known as mental or cognitive arithmetic, has been an active field of investigation [1].

From a functional point of view, there are at least three distinct specific processes involved in any instance of accurate mental calculation: execution of a calculation operation as can be represented by an arithmetic symbol (e.g. addition, + or subtraction, −); execution of supporting arithmetic operation procedures (e.g. carrying or borrowing during addition or subtraction) and retrieval of arithmetic facts (e.g. table facts like 3×7) [24,25,38]. Clinical reports of selective deficits in one of the three functional processes mentioned above suggest that they may be accomplished by relatively independent and separable subsystems. For instance, case reports of patients who cannot identify arithmetic symbols but can correctly perform the wrong operation (e.g. given an addition problem, give the correct answer to subtracting the numbers) indicates the relative independence of executing of arithmetic symbols [5,16,23]. Reports of patients who cannot monitor execution procedures

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or who have procedural dyscalculia suggest that the neural networks subserving execution of arithmetic procedures can be damaged separately [37,39]. Finally, there are many reports of patients with selective impairment of retrieval of arithmetic facts [7,9,10,12,18,26,30,38]. Together, these clinical observations suggest there are distinct domains and functionally independent components of mental calculation. However, the relative paucity of these studies limits the information they provide about the anatomical networks underlying these calculation processes. And in most cases, brain lesions are too large and conditions commonly too complicated to allow precise anatomical inferences.

Recently developed neuroimaging tools (fMRI and PET) provide another way to elucidate the neural processes underlying accurate mental calculation. With the help of these imaging tools, studies with normal subjects [2,6,11,19,21,22,27,28,31,33,36,40,41] have significantly deepened our understanding about the neural substrates of arithmetic processes and elucidated a hypothesized network for exact mental calculation that includes lateral prefrontal cortex, cingulate cortex, occipital cortex, insula and particularly the parietal cortex (including intraparietal sulcus and inferior parietal lobule), an area believed to be the key region in mental calculation. These studies demonstrate that the human brain employs a relatively specific neural network to accomplish exact calculation, which can be differentiated from the neural system that supports naming, comparing and evaluating numbers [6,19], and from the network that supports approximate calculation [11,36].

In this study, we focus on identifying the neural circuitry supporting two basic aspects of accurate mental calculation: execution of specific elemental arithmetic calculation types (e.g. as represented by a single arithmetic symbol) and the supporting arithmetic operation procedures (carrying and borrowing). We believe these two aspects are important because they represent the cognitive core of mental arithmetic. Theoretically, there are four basic types of arithmetic symbols that can be divided into two pairs, addition and subtraction, and multiplication and division. Each type is associated with specific rules [14]. One important question that remains to be answered is whether there are separate networks for each calculation type, a common network for all types or a combination of both specific networks combined with a shared common network. This question becomes more interesting for paired calculation types (like addition and subtraction) that have an intuitive inverse relation [32]. Thus, the first goal of this study is to test the hypothesis that the same neural network is activated during calculation of addition and subtraction problems.

To deal with large operands and more complicated computations, additional operational procedures are required. These operational procedures, like carrying and borrowing, greatly extend the range of mental arithmetic. There are specific rules for each of these procedures. For example, to calculate the problem 36+7 requires several steps. In one strategy, a person may compute 6+7, then maintain the intermediate result, 13, in working memory, then shift columns to the left and perform a second addition 3+1, remember the 4 to obtain the final result of 43. Clearly there are multiple possible strategies. These procedural operations are relatively automatic in educated adults who have had extensive training in school and repeated practice in daily life. The second goal of this study is to investigate the neural network supporting the arithmetic operation procedures of carrying and borrowing.

One challenge in studying arithmetic processes is to be able to distinguish true calculation from the arithmetic fact retrieval. Several recent neuroimaging studies investigating mental calculation have confounded these two processes by using calculation problems such as multiplication table and simple single-digit addition (3+1) [36,41]. The results from these studies may not represent brain regions involved in mental calculation but rather the difference between calculation processes that did or did not require arithmetic fact retrieval. In this study, we explicitly designed our calculation problems so that solving these problems requires real calculation, the answers cannot be retrieved from memory directly [4,10,22,37,38].

2. Materials and methods

2.1. Subjects

Sixteen healthy, right-handed subjects (seven males and nine females; ages 25–36 years, mean 28) participated in the study after giving written informed consent. All subjects had completed at least 15 years of education (all had at least a bachelor degree of science) and indicated that they had no difficulty calculating the problems in the allotted time. The Human Subjects Committee at Massachusetts General Hospital approved the protocol used in this study.

2.2. Experimental design

In this study, we used one pair of arithmetic operations (addition and subtraction) and two levels of operational procedure complexity (with and without carrying/borrowing) with first operands between 20 and 90 and second operands between 2 and 9 to investigate the neural substrates underlying the subsystems of accurate mental calculation. Solving these problems requires real calculation, the answers cannot be retrieved from memory directly [4,10,22,37,38]. The difficulty level of these problems was such that subjects achieved a high accuracy rate for the study allowing the use of reaction time measures to estimate problem difficulty [1]. We selected addition and subtraction because they are naturally paired and related [32].

There were four experimental conditions: addition without carrying (e.g. 35+3), addition with carrying (e.g. 35+7),