MATH 400: MATH, PSYCHOLOGY, AND NEUROSCIENCE

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ABSTRACT. For this project, I aimed to elaborate on how mathematics connects to psychology and neuroscience. This paper is organized into five parts. In part 1, I introduce the project by discussing my topic selection and research objectives. Part 2 considers my first research question: are some people inherently math-oriented? In this part, I discuss findings on the relationship between certain neurotransmitters and mathematical ability, a framework for understanding mathematical cognition, and the relationship between language and mathematical cognition. Part 3 considers my second research question: can anyone do complex mathematics? In this part, I discuss findings on the brains of mathematicians and the brain's capacity for growth in general. Part 4 considers the implications of psychology and neuroscience on math education. Following a brief discussion of how information discussed in parts 2 and 3 might be utilized in an educational setting, I discuss psychological findings relating to gifted programs and timed mathematics tests. I conclude in part 5 with a reflection. In this part, I discuss commentary on peer feedback, and areas for further study, including potential connections between my and my classmates' topics.

I. INTRODUCTION

1.1. **Topic Selection.** My own experiences learning mathematics inspired me to investigate the connections between math, psychology, and neuroscience. In my early years of education, I often had the idea of the "math brain" pushed on me. That is, I had the idea pushed on me that some people are implicitly more math-oriented than others. Funnily enough, as a child I was never told I had a math brain; in fact, as English was often my best subject, I was alternately encouraged to think of myself as being oriented toward the humanities. Luckily, this experience didn't discourage me from pursuing a degree and career in mathematics. However, I feel it easily could have. This thought is what initially piqued my interest in the relationship between math, psychology, and neuroscience: I wanted to know if there was any validity to the idea that people are implicity math-oriented. In my later years of education, I've had the pleasure of interacting with many people who share my passion for mathematics. Through them, I've noticed the polarizing effect math can have on people. Specifically, I've noticed that everyone I've met who studies or teaches math adores it; in contrast, nearly everyone I've met who does not study math despises it. This piqued my interest further, as it made me curious about how math works in your brain.

1.2. **Research Objectives.** This topic fits with the goals of our course, as it explores scientific implications on how we learn, understand, and perform mathematics. I had three main objectives in my research for this project. My first objective was to investigate the following question: do we have "math brains"? In other words, are some people implicitly math-oriented? My second objective was to investigate the following research question: can anyone do complex mathematics? In other words, could we all train ourselves to be math-oriented if we wanted to? My final goal was to explore the implications of psychological and neurological findings on math education.

II. DO WE HAVE "MATH BRAINS?"

2.1. **GABA, Glutamate, and Mathematical Ability.** GABA and glutamate are both neurotransmitters, or chemical messengers in the brain. Although both are often associated with learning and "school-based skills", how this association works in the human brain isn't fully understood, as much of what we know about GABA and glutamate comes from rodent experiments. We do know that GABA and glutamate have essentially inverted functions in the human brain. GABA is an inhibitory neurotransmitter, which means it blocks or inhibits certain brain signals; when GABA attaches to a protein in your brain, the GABA receptor, it produces a calming effect that can help with feelings of anxiety, stress, and fear. Glutamate is an excitatory neurotransmitter, which means it stimulates certain brain signals; glutamate is actually the most abundant excitatory neurotransmitter in the brain, and is involved with more than 90% of the brain's excitatory functions. Glutamate is also needed for your brain to create GABA. An imbalance of GABA and/or glutamate in the brain can lead to neurological or mental disorders such as Parkinson's, generalized anxiety, and more. Luckily, research has shown that, in cases of imbalance, effective methods exist to regulate the levels of GABA and glutamate in the brain; these methods range from changes in your diet to learning and attention-training activities. [1][2][3][4]

Roi Cohen Kadosh and his colleagues at the University of Surrey conducted a study to analyze the concentration of GABA and glutamate in the brain as it relates to mathematical ability over time. They administered math tests to 255 participants, ranging in age from six years old to college students, and measured participants' levels of GABA and glutamate. They then repeated this process with the same participants a year and a half later. Interestingly, the results of this study found different associations between GABA, glutamate, and math performance in younger versus older participants. In younger participants, an association was found between GABA levels and math performance; specifically, young children with high GABA levels did significantly better on the initial test. In older participants, an association was found between glutamate levels and math performance; specifically, older participants with low glutamate levels did significantly worse on the initial test. Although different associations were found, the researchers found that GABA and glutamate levels were good predictors of both the younger and older participants' performance on the test administered a year and a half later. In interpreting these results, Kadosh and his colleagues suggested that GABA and glutamate may have different roles at different stages of development; they posited that this would explain the differing associations between GABA, glutamate, and math performance in younger versus older participants. We can draw more concrete interpretations from the fact that GABA and glutamate levels consistently predicted math performance a year and a half later. This result suggests that it might be useful to stage learning interventions that specifically aim to regulate GABA and glutamate in students who struggle with math, and marks the study as a starting point for understanding mathematical ability. [1]

2.2. **Introduction to Gilmore's Framework for Mathematical Cognition.** In exploring whether some people are implicitly math-oriented, mathematical cognition is an important concept to consider. Mathematical cognition, put simply, is what happens in our brains when we learn or perform math. To improve our understanding of mathematical cognition, Camilla Gilmore and her colleagues formulated a framework for understanding how different components of mathematical cognition fit together. Their general argument was that previous frameworks for mathematical cognition have employed too broad a view of mathematics, and failed to categorize mathematical cognition; issues with alternative frameworks have made it difficult to analyze findings about mathematical cognition in a useful way. Their goal was to improve upon alternative frameworks to help us make sense of existing empirical evidence and identify important unanswered questions. Importantly, the framework is not intended to be a model of mathematical processing; we do not concretely, holistically know how mathematical processing works. However, implications about mathematical processing and how it works arise from the framework. [5]

Gilmore proposed three levels with which we should categorize mathematical cognition. The first, *overall mathematics achievement*, refers to "an individual's overall attainment in math, often measured by broad curriculum measures or [standardized measures]". The second, *proficiency with specific components of math*, refers to "an individual's performance in sub-components of mathematics for which it may be anticipated that they will use a consistent set of mathematical knowledge and skills". The third, *basic mathematical processes*, refers to "lower-level processes that underpin the specific components" we just described. A chart outlining examples of specific components of math and basic mathematical processes can be seen in Figure 2.2.1. Gilmore also notes that general cognitive skills and different learning experiences influence the development of each level of mathematical cognition, as well as the links between them. [5]

Specific components of mathematics	**Basic mathematical processes**
Count sequence knowledge	Single-digit number comparison
Number fact fluency	Multi-digit number comparison
Mental arithmetic	Non-symbolic magnitude comparison
Written arithmetic procedures	Number line estimation
Understanding of arithmetical relationships	Numerical order processing
Word-problem solving	Spatial-numerical associations
Adaptive strategy selection	Place-value understanding
Algebraic thinking	Intuitive geometrical knowledge
Solving algebraic word problems	Pattern recognition
Composition of shapes	Analogical reasoning

Figure 2.2.1 [5]

Gilmore's framework adds structure and specificity to how we think about mathematical cognition; alternative frameworks have been much more vague in their categorization of mathematical cognition, or lack concrete categorization altogether. One issue Gilmore notes about alternative frameworks is their tendency to focus only on broad measures of mathematics achievement. According to Gilmore, "Use of broad measures of mathematics achievement, which incorporate a range of specific components of mathematics, makes it difficult to identify the specific mechanisms by which cognitive factors may play a role in learning or performing mathematics." In other words, proficiency with a variety of specific components of mathematics is needed to have high overall mathematics achievement; for each of those specific components, different cognitive factors may or may not play a role in proficiency. So when we focus too much on overall achievement, mostly measured by things like standardized tests, we can't easily identify the specific components that have the biggest impact on overall achievement, and in turn, can't easily identify the relevant cognitive factors that play a role in our ability to do math. Another issue Gilmore notes about alternative frameworks is that even when they try to categorize mathematical cognition, they often conflate overall achievement with proficiency with certain components of mathematics; specifically, many frameworks use "measures of proficiency with specific components of mathematics as synonymous with overall mathematics achievement". To make sense of this, Gilmore provides the following example: suppose we have a study in which participants are asked to retrieve number facts, and a study in which participants are asked to perform a written algorithm for multi-digit multiplication. Under such an alternate framework, the participants' ability to perform their given tasks would be used as a measurement of their overall mathematical ability in both studies. This is an issue, as we would not expect the cognitive skills involved in retrieving number facts and those involved in performing a written algorithm for multi-digit multiplication to be exactly the same. Gilmore believes that frameworks conflating these levels may explain a lot of conflicting findings in existing studies. [5]

2.3. **Existing Evidence within Gilmore's Framework.** Now we will consider existing evidence within Gilmore's framework, and examine the implications that arise. First, we will discuss evidence that will force us to think about how basic mathematical processes connect to proficiency with specific components of mathematics. Studies suggest that there is a relationship between many basic mathematical processes and proficiency with specific mathematical components. The example we'll consider to understand this pertains to the basic mathematical process of magnitude comparison. Numerous studies have found that magnitude comparison skills are associated with mental and written arithmetic abilities. Individual studies have found associations between magnitude comparison skills and proficiency with arithmetic strategy selection, written multi-digit arithmetic, and geometry. In general, that a set of basic mathematical processes is necessary for proficiency with a given specific component of mathematics is a fairly natural conclusion, and Gilmore's framework generally implies it. However, it is important not to conflate basic mathematical processes and general cognitive skills, as general cognitive skills do not explain the relationship between basic math processes and proficiency with specific components. Specifically, in many studies, the relationships between basic mathematical processes and proficiency with specific components of mathematics stay the same after controlling for cognitive skills. That being said, there are some exceptions; several studies have demonstrated that the relationship between magnitude comparison and proficiency with arithmetic is explained by inhibitory control, for example. [5]

Next, we will discuss evidence that will force us to think about how proficiency with specific components of mathematics relates to overall mathematics achievement. An important note about the relationship between these two levels is that overall mathematics achievement does not tell us a lot about an individual's proficiency with specific components of mathematics. That being said, for a person to have high overall achievement in mathematics, they need to be proficient with some specific components of mathematics. Studies have suggested that some specific components of math are more closely associated with a person's overall math achievement than others. In early years of schooling, it has been shown that proficiency with number fact retrieval, arithmetical skills, understanding of arithmetical principles, and understanding of fractions are the best predictors of overall mathematics achievement. However, the components of math that most accurately predict overall achievement vary throughout the years and stages of a person's schooling; in adolescence, for example, algebraic thinking is more closely associated with overall achievement than the symbolic number knowledge associated with overall achievement in earlier years of schooling. These findings are also complicated by the fact that research about these specific components of mathematics as they relate to overall mathematics achievement has overwhelmingly focused on subjects' knowledge and skills more than their conceptual understanding. Many researchers and educators have suggested that conceptual understanding may be a better predictor of overall achievement than procedural measures. However, it is very difficult to measure a person's conceptual understanding, and Gilmore notes that agreed-upon methods for measuring conceptual understanding do not exist. This is one area of Gilmore's framework that exposes something we need to be asking more questions about and trying to investigate further, then. [5]

Next, we will discuss how general cognitive abilities connect to Gilmore's proposed levels of mathematical cognition. General cognitive ability has an impact on each level. The general cognitive abilities that are most heavily researched in the context of mathematical cognition are executive function skills and working memory. Executive function skills are necessary to control one's behavior; for example, attention control is an executive function skill. Studies have shown that these skills are important for overall math achievement and proficiency with specific components of math. This could explain some variance amongst students in overall mathematics achievement that proficiency with specific components of math cannot; especially if we measure overall achievement with curriculum-based measures such as standardized tests, we might see students who show high proficiency in various components of math achieving at the low end overall because they struggle with executive function skills such as paying attention and sitting still. However, Gilmore notes the potential shortcoming that these studies overwhelmingly focus on arithmetic; we can't necessarily draw conclusions about the role of executive function when it comes to learning other domains of math. Working memory is a type of short-term memory necessary for things like reasoning and language comprehension. Unsurprisingly, this has been found to be an important cognitive function for learning and performing mathematics at all of the levels Gilmore describes. [5][6][7]

Finally, we will discuss the impact of mathematical learning experiences on each proposed level of mathematical cognition. Unfortunately, most of the research investigating this connection has considered how individual learning experiences connect to overall mathematics achievement. Hence, there's a lot of work to be done to understand how different learning experiences can impact basic mathematical processes and proficiency with specific components of mathematics. That being said, there are some interesting results to consider. For example, studies have shown that children conceptualize equivalence in two ways. Some conceptualize it relationally, meaning they understand expressions on either side of an equal sign have the same value. Others conceptualize it operationally, meaning they understand equal signs as indications of where answers should go. Children with a relational conceptualization of equivalence tend to have higher overall mathematics achievement. This relational conceptualization can be fostered by using mathematical symbols more flexibly. For example, in a classroom where students always see equalities expressed like "2+5=7", "10+1=11", "3+6=9", etc, they will be more likely to develop an operational understanding of equality. But, if we vary the order used to represent these symbols, occasionally writing, say, "7=2+5", "11=10+1", "9=3+6", etc, students are more likely to develop a relational understanding of equality. Informal learning experience is another thing that is thought to influence basic mathematical processes, but overall, little research has been done on this subject; this is another area that Gilmore's framework exposes as being underexplored. [5]

2.4. **Language and Mathematical Cognition.** It is also thought that cultural differences may influence a person's mathematical cognition. For example, it has often been suggested that a person's native language may impact the way they understand mathematical concepts. A 2003 study investigated the acquisition of the base-ten system among children who spoke different languages. Specifically, this study investigated how children who natively spoke Chinese, Japanese, or Korean represented numbers as compared to children who natively spoke French, Swedish, or English. Each child was given a set of blocks, each of which represented the number one, and logs, which represented the number ten. They were then asked to use the blocks to represent a variety of numbers. Overall, the results indicated that children who natively spoke Chinese, Japanese, or Korean utilized the logs, while children who natively spoke French, Swedish, or English largely represented each number using only blocks. Researchers took this to mean that children who natively spoke Chinese, Japanese, or Korean had a better understanding of the base-ten system; they further hypothesized that this difference could be explained by the nature of counting in Chinese, Japanese, and Korean. Specifically, they suggested that native speakers of Chinese, Japanese, and Korean have a better understanding of base-ten because, in these languages, single digits serve as building blocks for numbers after ten. Notably, however, the children studied went to schools that taught math in different ways, making it difficult to distinguish the influence of language on their performance from the influence of varied teaching methods. [8]

A 2008 study attempted to distinguish between the influence of language and teaching methods on mathematical performance. This study tested Chinese and British primary school childrens' proficiency in arithmetic. They bypassed the issue of differing teaching methods by testing Chinese students in Hong Kong; the Hong Kong educational system is based upon the British system of teaching due to its history as a British colony. Although researchers expected native speakers of Chinese to outperform speakers of English in every metric, the study found that language has a "specific rather than pervasive" influence on differences in arithmetic performance. In terms of Gilmore's framework, the results of this study suggest that a person's native language may influence their proficiency with specific components of mathematics, but not necessarily their overall achievement in mathematics. [5][8]

A 2023 neurological study compared the brain connectivity in native German and Arabic speakers. This study found that native German speakers exhibited "stronger connectivity in an intra-hemispheric frontal to parietal/temporal dorsal language network known to be associated with complex syntax processing". It also found that native Arabic speakers exhibit "stronger connectivity in the connections between semantic language regions, including the left temporoparietal network, and stronger inter-hemispheric connections via the posterior corpus callosum connecting bilateral superior temporal and inferior parietal regions". In terms of Gilmore's framework, the results of this study suggest that a person's native language may offer them an advantage when it comes to a particular general cognitive skill; however, these results tell us relatively little about the extent to which, or manner in which, a person's native language influences their basic mathematical processes, proficiency with specific components of mathematics, or overall mathematics achievement. [5][9]

III. CAN ANYONE DO COMPLEX MATHEMATICS?

3.1. **The Brain of a Mathematician.** A 2016 study investigated how a mathematician's brain functions, and whether it functions differently than a non-mathematician's brain. The study compared the brain activity of mathematicians and nonmathematicians of the same academic standing. Each subject was put in an MRI scanner and shown 72 high-level math statements. These statements were divided evenly among algebra, analysis, geometry, and topology. They were also shown 18 high-level nonmathematical statements. For mathematicians only, "listening to math-related statements activated a network involving bilateral intraparietal, dorsal prefrontal, and inferior temporal regions of the brain. This circuitry is usually not associated with areas involved in language processing and semantics, which were activated in both mathematicians and nonmathematicians when they were presented with nonmathematical statements". Interestingly, previous research has found that the same network activated in the mathematicians' brains when they viewed math-related statements is active when performing very basic arithmetic or even just seeing numbers on a page. The results of this study, when considered with the results of previous studies, suggests a link between advanced and basic mathematical thinking. Stanislas Dehaene has devoted his studies to the field of mathematical cognition, and more specifically, whether it is to some extent intuitive. He has found that humans are born with some innate sense of numbers. However, we still don't know how the connection between this innate "number sense" and high-level math is formed. Regardless, this study presents a very interesting question about how this connection is formed. Specifically: "is an innate capability to recognize different quantities – an intuitive 'number sense' – the biological foundation on which the capacity to master group theory can be built?" [10]

3.2. **The Brain's Capacity for Growth.** Brain plasticity, or the ability of the brain to change over time, is another interesting concept for us to consider. Our brains have enormous capacity for growth and change at all stages of our lives. This is evidenced by studies investigating the brains of London black cab drivers. London black cab drivers must pass a test called “The Knowledge”; this notoriously difficult test requires memorization of all the roads within a 20-mile radius of Charing Cross, and every connection between them. Neuroscientists found that the spatial training undergone by London black cab drivers caused areas of their hippocampus to significantly increase. They also found that when the drivers retired, these areas shrunk back down to their original size. These studies were significant for many reasons. For starters, they showed significant brain growth and change in adults of a wide range of ages. On top of this, the area of the brain that saw significant change – the hippocampus – is extremely important for spatial and mathematical thinking. Before these studies, most people thought that our brains were fairly fixed in their development; since these studies, further research has been done to investigate brain plasticity. This research has shown extensive brain growth in people of all ages. Evidence also suggests that brain growth is stimulated by engagement with challenging content, making mistakes, and correcting them. [11]

IV. MATH EDUCATION

4.1. **Implications of Previously Discussed Findings.** The findings we have discussed concerning our two research questions are undoubtedly relevant to math education. The study concerning the relationship between GABA and glutamate and math ability suggests the usefulness of learning interventions that aim to regulate GABA and glutamate in students who struggle with mathematics. Gilmore’s framework exposes the lack of research done on the relationship between teaching methods, basic mathematical processes, and proficiency with specific components of mathematics. Existing evidence within Gilmore’s framework has several interesting implications for math education. Research regarding the relationship between proficiency with specific components of mathematics and overall achievement in mathematics serves as a starting point for identifying which components of mathematics are most important for students to understand at different stages of schooling; research regarding the relationship between general cognitive abilities and mathematical cognition suggest the importance of executive function skills and working memory in math performance; research regarding students' understanding of mathematical equivalence suggests the usefulness of flexibly representing expressions in the classroom. Our knowledge of brain development and plasticity suggests that struggling with math problems – making mistakes, and correcting them independently instead of being told the answer – would stimulate the growth and development of students' brains. [1][5][11]

4.2. **Gifted Programs.** Evidence suggests that gifted programs are harmful to all students involved. Children who are told, however indirectly, that they are "ungifted", will experience shame and academic anxiety as a result of such programs. On the other hand, children who are told they are "gifted" are also hurt by these programs. This type of academic validation, offered to students at such a young age, gives them the impression that their success in school comes naturally; when these students inevitably run into a concept that they don't understand, then, it comes as an unexpected shock. They don't know how to cope – they don't know how to struggle with the content at hand, and as such, are robbed of an opportunity to stimulate brain growth by making and correcting mistakes. The same detrimental impacts have been discovered for students exposed to fixed-ability language in general. Telling students that they are "gifted" or "ungifted", have "math brains" or are "humanities-oriented" are all examples of fixed-ability language. This type of language has "contributed to our nation's fear and dislike of mathematics." [11]

4.3. **Timed Math Tests and Drills.** Arguments have been made in favor of and against timed mathematics tests and drills. Those in favor argue that these tests free up students' working memory to handle more complicated math problems by making basic calculations automatic. Those in opposition argue that these tests cause students to have so much anxiety that they overwhelm their working memory and prevent learning. Interestingly, there is no empirical evidence that timed math tests cause anxiety. However, it's very hard for researchers to measure math-related anxiety in these settings, as a lot of the physical symptoms of adrenaline and stress – such as a high heart rate – are the same. First-person accounts suggest that these tests do cause anxiety. Students have reported getting stressed and forgetting things, or even deciding they aren't a "math person" partway through these tests and losing interest in math as a subject later on. As an alternative to timed tests and drills, arguments have been made in favor of lower-stress activities such as ungraded timed assignments or games. [12]

V. REFLECTION

5.1. **Peer Feedback.** After giving a talk on this subject, my peers seemed most engaged by my discussion of math education. Interestingly, while we mostly agreed that gifted programs aren't pedagogically sound, there was a spirited debate on the usefulness of timed math tests and drills. Based on this discussion, I think my presentation could have been improved if I had spent slightly more time talking about math education, and provided a more thorough account of research done on timed math tests and drills; it seems such a change would have suited my audience. The feedback offered by my peers on our online discussion board was largely positive;

students felt that the talk was engaging and easy to understand. The discussion board also seemed to confirm my impression that my peers were particularly interested in the math education portion of the talk, as quite a few people had thoughts to add on this subject. I also received a couple of suggestions for areas of further study.

5.2. **Areas of Further Study and Connection.** My peers suggested or inspired two areas of further study for this subject. One student suggested that, in my investigation of whether people are implicitly inclined to do math, it may be interesting to explore mathematical cognition in math prodigies. I agree that if I were to expand my research, this would be a useful line of inquiry that would add nuance to the findings I've presented thus far. A couple of my peers also mentioned that their elementary schools included non-traditional gifted programs; one person mentioned that the program was not called "gifted", and another mentioned having a gifted program that pulled one or two students out of class on occassion. It seemed that calling the program by a different name, and decreasing its scale, dampened the negative effects of gifted programs for these students. Hence, if I were to expand my research, I'd be interested to investigate whether gifted programs can be altered to counteract their negative effects, or if it is in everyone's best interest that they be abolished entirely.

There are several interesting connections between my topic and those of my peers that I would also like to investigate if I were to expand my research. One of my peers did a presentation on math education, focusing on teaching methods used around the world. My topic has obvious applications in this one; it would be interesting to see which teaching methods psychologists and neuroscientists think are the most effective for learning mathematics, and what research is yet to be done on this subject. Another one of my peers presented the math behind the board game Go. I think it could be interesting to examine whether talented Go players are proficient in mathematics, and if so, which areas. Several of my peers gave presentations relating to computer science. As subjects that often intertwine, I would be interested to know which neural pathways and areas of the brain are engaged by learning and performing both math and coding, and to what extent these pathways and areas differ. I also think a connection could be made between this topic and my first presentation topic, crochet in mathematics. I could explore the cognition involved in fiber art as compared to mathematical cognition, investigate the potential usefulness of crochet as a math education tool, or even compare the brain activity involved in performing and learning crochet versus math.

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