ABSTRACT

Title of Dissertation: INHIBITION IS KEY: A COGNITIVE APPROACH TO SUCCESSFUL WORD PROBLEM SOLVING

Joshua Benjamin Jaffe, Doctor of Philosophy, 2024

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Numerical competency and reading comprehension skills are necessary, but insufficient for word problem success. Depending on the word problem structure, successful problem solving may require inhibiting the seemingly obvious and correct answer. Inhibitory control plays a significant role in processing and solving word problems. Through classroom practices and textbook problems, I argue that individuals form associations between relational terminology and specific mathematical operations (“more” for addition and “less” for subtraction), and the notion that all numerical values in a problem must be used to produce an answer. In this study, I proposed an inhibitory performance-based model that posits two approaches to problem solving: (a) a successful approach where solvers inhibit mathematical associations and form appropriate set schemas to conceptualize semantic relations, and (b) an association approach where solvers do not inhibit associations and therefore may have an inaccurate understanding of the semantic relations. To test the model, data were analyzed from 105 undergraduate students at the University of Maryland. The study consisted of four sections: cognitive skills, word problems, domain-specific inhibitory control tasks, and a semi-structured interview. The word problem section included problems that were both consistent and inconsistent with an individual's operational and numerical associations. Overall, the quantitative results identified that participants performed significantly worse on inconsistent problems. Further, the data suggest that failure to correctly answer inconsistent problems may be due to inhibitory control rather than other cognitive skills. The qualitative data indicated that a vast majority of participants believed in both mathematical associations and remembered classroom experiences that may have contributed to these beliefs. While inhibitory control has been suggested to play a significant role in word problem performance, this is one of the first studies to explicitly examine the relationship through domain-specific inhibitory control tasks and an interview. These results guide a path for future research to examine how individuals develop mathematical associations and for interventions to dissuade their usage.

INHIBITION IS KEY: A COGNITIVE APPROACH TO SUCCESSFUL WORD PROBLEM SOLVING

By

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Dedication

To Maddy

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I am extremely proud of what I have accomplished during my academic career at the University of Maryland, and I am excited to see what the future holds. However, as I am docked at the port of indecision waiting for my next academic adventure, I think I will first search for my lost shaker of salt.

But first, enjoy reading about word problems!

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"There are 125 sheep and 5 dogs in a flock. How old is the Shepherd?"

"125 plus 5 equals 130… this is too big, and 125 minus 5 equals 120 is still too big… while… 125 divided 5 equals 25… that works… I think the Shepherd is 25 years old."

Reusser, 1988

Chapter 1: Introduction

Word problems, mathematical problems where the relevant information needed for problem solving is presented in language form rather than in mathematical notation, play a crucial role in connecting mathematics with our daily lives (Boonen et al., 2016; Verschaffel et al., 2000). Through infinite scenarios, word problems help individuals appropriately understand and navigate the behaviors of real-world situations. Whether it is calculating the statistics of your favorite athlete, shopping for groceries, or completing your taxes, the skills an individual can learn through solving word problems are fundamental to one's academic and professional success (Burkhardt, 1994; Verschaffel et al., 2002).

This practical usage has long justified the presence of word problems in all mathematical curricula and has emphasized the importance of developing proper mathematical modeling and critical thinking skills (Blum & Niss, 1991; Verschaffel et al., 2010). However, word problems have shown to give individuals of all ages difficulty (e.g., Boonen et al., 2016; Cummins, 1991; Hegarty et al., 1995). Children encounter word problems in early formal education and this exposure continues through all subsequent mathematics classes. In fact, many word problem lessons may be taught in parallel with numerical arithmetic problem lessons due to requiring similar computational and arithmetic skills. Yet, word problem performance has not always perfectly correlated with numerical arithmetic problem performance (e.g., Pongsakdi et al., 2019). Early research identified that young students performed significantly worse on simple word problems compared to numerical arithmetic problems, suggesting that the linguistic component made the problem-solving process more complex, which hindered numerical processing and overall word problem performance (Carpenter et al., 1980; Kouba et al., 1988).

Understanding how individuals construct mental models of the linguistic component has been at the center of word problem research (e.g., Cummins, 1991; Kintsch & Greeno, 1985). Unlike numerical arithmetic problems which have a consistent structure (i.e., A +/- B = C), word problems have no set requirements regarding word count, the order of characters and objects, or if irrelevant numerical information can be embedded within the problem. Therefore, having the luxury to easily identify the mathematical operation and numerical values in numerical arithmetic problems is not always afforded in word problems (Stern, 1993; Wang et al., 2016; Xin, 2018).

Mathematical modeling, the ability to create mathematical representations of real-world applications, has helped researchers and practitioners understand the word problem solving process (Leiss et al., 2019; Verschaffel et al., 2010). Verschaffel and colleagues (2010) proposed that there are several phases that solvers must navigate. They must be able to identify key elements of the problem, construct a mathematical model of the relations between characters and objects, transform the model to an equivalent numerical problem, solve, and then evaluate if the answer is an appropriate outcome. Successful mathematical modeling and word problem performance is the result of having the appropriate cognitive skills (e.g., reading comprehension, numerical competency, working memory capacity, and inhibitory control; Daroczy et al., 2015; Kintsch & Greeno, 1985; Vilenius-Tuohimaa et al., 2008; Zheng et al., 2017), and utilizing an appropriate strategy (Hegarty et al., 1995).

Educational practices can significantly influence students' strategic approaches (Callejo & Vila, 2009; Hill et al., 2005). However, recent research has suggested that classroom practices may be inhibiting students from developing proper mathematical models (Verschaffel et al., 2020). Gerofsky (2009) argues that modern lessons fail to bridge the gap between real-life and mathematics; lessons are often neglecting the situational narrative and focusing on the mathematical structure (Chapman, 2006; Depaepe et al., 2010; Rosales et al., 2012). Further, Verschaffel et al. (2010) suggest that emphasizing the mathematical structure has resulted in lessons using suboptimal strategies to identify the mathematical operation(s) and numerical values involved. For example, the mathematical association, or heuristic, "more for addition and less for subtraction," has been implemented and taught in classrooms despite the mathematical operation being dependent on the relational terminology's placement between characters (Pape, 2003; Powell et al., 2022). Similarly, solvers learn to associate that all numerical values presented must be used and manipulated for a correct answer despite Verschaffel et al. (2020) arguing that real-world word problems can often involve vague conditions that cannot be solved by applying mathematical operations to the numerical data presented.

The ability to inhibit mathematical operational and numerical value associations, which I refer to as domain-specific inhibitory control, may play a significant role in word problem success (Lubin et al., 2016; Van Dooren & Inglis, 2015). The current dissertation focused on these associations and aimed to further investigate how solvers decipher the operation and numerical values needed for successful problem solving. The next section examines theoretical frameworks specific to the word problem solving process and how environmental factors can influence problem-solving strategies. The chapter concludes with a proposed inhibitory performance-based word problem model that accounts for environmental factors regarding mathematical associations and an overview of the current study.

Theoretical Considerations

This section examines the following theoretical considerations to further understand the word problem solving process and how individuals develop their strategic approaches: (a) Information Processing Theory which outlines how solvers process word problems, and (b) Bandura's Social Learning Theory which highlights how students may be influenced by their academic environment.

Information Processing Theory

Problem solving is a universal human activity. Individuals are presented with challenges every day and must rely on both sensory input and higher level cognitive functions to complete their goals (Simon, 1978). Information Processing Theory is a cognitive approach to understanding how the mind learns and accomplishes problem-solving tasks (Miller, 1956). Rather than reflexively responding to stimuli, this theory focuses on how individuals process information. Like computer processors, there is a set order to the problem task process: (a) receiving information through sensory input, (b) processing and manipulating information via working memory and integrating the current stimuli with previously encoded information (e.g., long-term memory; Lutz & Huitt, 2003), and (c) utilizing the integrated information to elicit a response (Simon, 1979).

Information Processing is an umbrella term to understand the cognitive problem-solving process. However, it has played a role in understanding the cognitive mechanisms for word problem solving. Kintsch and Greeno's (1985) arithmetic word problem model focused on the integration between text-comprehension theories (e.g., Van Dijk & Kintsch, 1983) and strategic problem-solving approaches (e.g., Brown & Burton, 1978). Built upon Information Processing models, solvers must first translate the visual stimuli (i.e., the text) into propositions and organize propositions into set schemas in working memory with the categorical information of object (e.g., noun), quantity (e.g., numerical value of objects), specifications (e.g., owner, setting, time), and role (e.g., was the quantity an initial set, did it change throughout the situational narrative, is it the result of a change?). As solvers progress through the text, they can either build upon established sets, or form new schemas that may displace previous sets (Kintsch & van Dijk, 1978). This allows solvers to construct mathematical models of the relations between characters and objects. In this process, solvers determine what information from the text is relevant, what information is irrelevant, and what previously encoded information not presented in the text is needed for problem solving. Finally, to determine which numerical values and operation(s) are needed for successful problem solving, the solver compares the relations between the set schemas constructed in the previous stages (Figure A1 in appendix).

Social Learning Theory

Social Learning Theory serves as a helpful theoretical view to understand how individuals develop strategic approaches for word problem solving. Mathematical modeling and a solver's strategic approach are influenced by social processes (Woods et al., 1995). Teachers hold beliefs about what constitutes successful word problem solving; their lessons reflect these ideas and influence how their students construct mathematical models (Callejo & Vila, 2009; De Corte et al., 2008; Stipek et al., 2001). Social Learning Theory is a process of learning new behaviors through observing and imitating others (Bandura, 1969, 1977). This framework focuses on: (a) the physical act of imitating, and (b) why an individual decides, or is intrinsically motivated, to reproduce an observed behavior. Both constructs contribute to how students approach word problems.

Physical Mechanisms. To imitate a behavior, one must be able to physically see the behavior occur, remember the features of the specific behavior, and be able to reproduce the behavior (Bandura, 1969). From an educational perspective, this process can occur through structured lessons where teachers give explicit instructions and/or information to their students (De Corte et al., 2011; Gravemeijer et al., 2011). Chapman's (2006) observational-based research identified that when experiencing new types of problems, most teachers first model strategic approaches and then provide similar problems for students to complete (e.g., direct instruction). Teachers' lessons can emphasize different word problem solving strategies and influence how students construct mathematical models (e.g., Fuchs et al., 2010; Verschaffel & De Corte, 1997). For example, teachers that use the "Realistic Mathematics Education" approach highlight the importance of relating mathematics to daily-life activities. Lessons emphasize comprehending the situational narrative, understanding part-whole relations, and analyzing the authenticity of their produced answer (Makonye, 2014; Zakaria & Syamaun, 2017). In observational-based and intervention studies, students that were exposed to this approach were more likely to elicit more authentic mathematical models and incorporate real-life knowledge in their problem solving (Pongsakdi et al., 2016b; Verschaffel & De Corte, 1997). Similarly, students who partook in schema-broadening instruction became better at building schemas of the situational narrative and comprehending the relations between characters and objects prior to solving the problem (Schumacher & Fuchs, 2012). Students who received more paradigmatic-oriented lessons that focused on the numerical and calculation components tended to neglect the situational narrative (See chapter 2; Depaepe et al., 2014; Fuchs et al., 2010).

Motivational Mechanisms. An individual's decision to imitate a behavior is not solely based on if they can physically or cognitively reproduce the behavior. Individuals consider: (a) the model that first initiated the behavior, and (b) the consequence, or feedback, for producing the behavior.

Model. An individual's relationship with a model influences how likely they are willing to imitate the behavior. In a student-teacher relationship, the students' understanding that the teacher holds more knowledge and can help them succeed academically is a sufficient reason to imitate the behavior and lesson plans (Tinto, 2012; Zhou & Guo, 2016). From a socio-cultural perspective, teachers act as a more knowledgeable other and have the ability to transfer information through instruction (Vygotsky, 1978). Therefore, to succeed, individuals benefit from being engaged in the classroom and reproducing the strategic approaches taught by their teacher(s) (Hendry et al., 2016).

Feedback. In an educational setting, achievement can be quantified by letter and/or numerical grades. Grades are assigned by how well you achieved the teachers' goals, and in the case of word problems, how often you produce the correct answer. Clement and Battista (1990) argue that when teachers provide students with specific mathematical methods, students should imitate these methods to achieve the teachers' objectives. When students underachieve, feedback from teachers allow students to adjust their behavior which encourages academic success (Tinto, 2012). Further, empirical evidence has shown teachers' beliefs influence their grading practices (Verschaffel et al., 1997; Widiastuti, 2018). Therefore, students may benefit academically by listening to their teachers' feedback and following their lesson plans (Hendry et al., 2016).

The Proposed Inhibitory Performance-Based Model

Existing empirical work and theoretical models have laid the building blocks to what constitutes a successful problem solver (e.g., Cummins, 1991; Kintsch & Greeno, 1985; Verschaffel et al., 2010). However, evidence has demonstrated that college-aged and college-educated individuals – individuals who have had years of mathematical word problem exposure and theoretically have all the cognitive tools to be successful – have difficulty with problems that are inconsistent with their mathematical associations (e.g., "more" being used in a subtraction problem; Daroczy et al., 2015; Gros et al., 2019; Hegarty et al., 1992, 1995). Lave (1992) argues that Information Processing models fail to account for all aspects of an individual's problem-solving process. Problem solving is a human activity and models must consider an individual's practices and experiences within the classroom. Therefore, models must account for the optimal and suboptimal strategies that learners develop through word problem lessons and the word problems they encounter.

Hegarty et al.'s (1995) problem solving approach posits that individuals must transform the word problem to an equivalent numerical problem for successful solving. This requires identifying: (a) the mathematical operation, and (b) which numerical values are needed to produce an answer. The present dissertation study argues that classroom experiences and textbook problems encourage solvers to use their mathematical associations to identify the operation and numerical values needed to elicit correct responses. Verschaffel et al. (2020) proposed that solvers construct strategies based on the problem types they encounter. When experiencing a problem that is inconsistent with their mathematical associations, solvers may not have the cognitive flexibility to inhibit their predominant strategies (Hegarty et al., 1992;

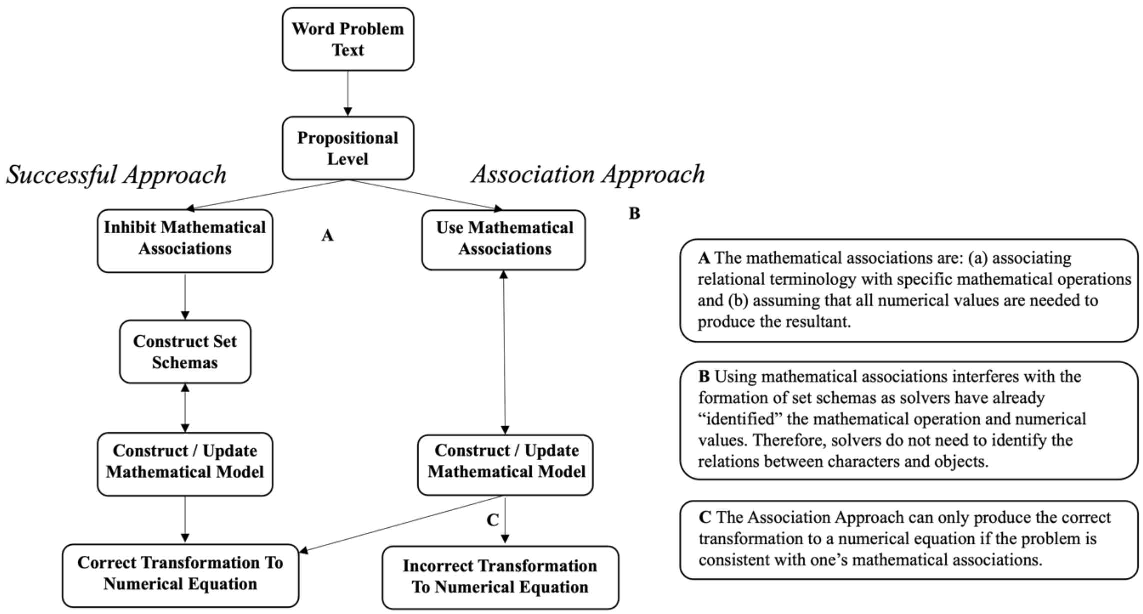
Passolunghi et al., 2022). To construct an appropriate mathematical model, solvers must inhibit their mathematical associations (Verschaffel et al., 2010).

The proposed inhibitory performance-based model, which I have recently published in *Educational Psychology Review* (Jaffe & Bolger, 2023), offers revisions to Kintsch and Greeno's (1985) framework. As solvers progress through the problem, they still translate the text into propositions and organize propositions into set schemas. However, as solvers encounter relational terminology and/or numerical values, they reach a critical juncture(s). They can either inhibit, or use, their mathematical associations. Inhibiting mathematical associations allows solvers to continue building set schemas and constructing mathematical models of the relations between characters and objects (Kintsch & Greeno, 1985; Verschaffel et al., 2010). From there, solvers evaluate the relations between set schemas to determine the mathematical operation and numerical values needed for successful solving. The proposed model calls this route the "Successful Approach."

Using mathematical associations, whether individuals have difficulty inhibiting or actively choose to not inhibit, may interfere with current set schemas, and prohibit the construction of future schemas. Mathematical models may develop prematurely due to not appropriately identifying and examining the relations between characters and objects. Depending on the structure of the problem, solvers may have already determined the mathematical operation and numerical values needed prior to reading the complete problem. The model calls this route the "Association Approach." Of note, the association approach can still produce correct answers, only if the problem is consistent with the solver's mathematical associations (e.g., "more" representing addition; no extraneous numerical information; Figure 1).

Figure 1

Proposed Inhibitory Performance-Based Model



The proposed model aims to better explain the word problem solving process. For the past 50 years, many word problem models have been introduced to the field (e.g., Boonen et al., 2013; Capraro et al., 2011; Hegarty et al., 1995; Kintsch & Greeno, 1985). However, to my knowledge, no models consider how human activity and classroom practices can influence problem solving. Only a few incorporate a solver's strategic approach. Models like Hegarty et al.'s (1995) problem solving approach demonstrate that individuals may use a keyword method to identify the mathematical operation. Yet, they do not explain why solvers use the keyword method (See chapter 2; Briars & Larkin, 1984). Understanding how solvers approach word problems and why they use suboptimal strategies may allow researchers and practitioners to approach word problem difficulty from an inhibitory control perspective (Brookman-Byrne et al., 2018).

The proposed model also has the potential to frame future research by better connecting research and practice. Chapter 2 investigates educational practices that may lead learners to further use and solidify their mathematical associations. For example, Powell et al. (2022) point out that many classrooms use keyword posters to guide students into identifying the mathematical operation without having to understand the situational narrative. Further, Verschaffel et al.'s (2000) textbook analysis identified that over 90% of problems could be correctly solved by an individual using their mathematical associations. Developing practices that dissuade individuals from using their mathematical associations, whether through explicit instruction and/or exposure to word problems that are inconsistent with their associations, may elicit more cognitively demanding, but appropriate strategies for problem solving.

Study Overview

To test the proposed inhibitory control model, the present study aimed to provide a foundational understanding of the relations between domain-specific inhibitory control and word problem performance by replicating previous findings as well as adding novel contributions to the field. 105 undergraduate students participated in the present study and completed four sections. To directly test the performance-based outcome of the proposed model, participants completed a series of word problems that were both consistent (e.g., "more" being used in an addition problem) and inconsistent (e.g., "more" being used in a subtraction problem) with their operational and numerical associations. To explore the relationships between domain-specific inhibitory control and word problem solving, participants underwent a battery of domain-general cognitive tests and domain-specific inhibitory control tasks. The objective was to investigate whether domain-specific inhibitory control is essential for successful word problem solving and to understand if it could predict word problem performance while controlling for other cognitive skills. Finally, to gain insight into participants' mathematical association beliefs, classroom experiences, and overall understanding of word problems, the study concluded with a semi-structured interview. Understanding how individuals process word problems and their beliefs towards mathematical associations may have significant theoretical and educational implications.

Aims And Hypotheses

The ***first aim*** of the present study was to examine performance on problems that were consistent with mathematical associations compared to inconsistent problems and investigate why participants produced incorrect responses. To explore this aim, analyses were conducted on the following research questions: *Do individuals elicit stronger accuracy and quicker response times on problems that are consistent with their mathematical associations* and *are incorrect responses on inconsistent problems consistent with their mathematical associations?*

There were several hypotheses for the first research aim. First, I predicted participants would elicit stronger performance and quicker response times on problems that are consistent with their mathematical associations compared to problems that are inconsistent. While most work has been conducted on children and adolescents (e.g., Boonen et al., 2013; Jiménez & Verschaffel, 2013), I expected similar patterns to emerge with an undergraduate population. Regarding incorrect responses, I predicted participants were more likely to make incongruent errors (errors that are consistent with their mathematical associations; e.g., used the wrong operation or used the irrelevant numerical value) than miscalculation errors (all incorrect responses that were not incongruent errors; e.g., 12 + 4 = 18) on inconsistent problems. However, for consistent problems, they were more likely to make miscalculation errors as no parts of the problems contradicted their beliefs. Finally, the inhibitory control model proposes two distinct pathways to problem solving, a successful approach and an association approach. Each pathway may result in accuracy differences. I expected two distinct groups to emerge from the sample that were consistent with each pathway. Group A would demonstrate similar performance on all problem types (i.e., successful approach). Group B would elicit stronger performance on consistent problems and weaker performance on inconsistent problems (i.e., association approach). Individuals in group B may not be able to discern inconsistencies embedded within problems as they are not inhibiting their associations (Hegarty et al., 1992; Shum & Chan, 2020).

The ***second aim*** of the present study was to investigate how domain-specific inhibitory control relates to word problem performance and the production of incongruent errors. To explore this aim, analyses were conducted on the following research questions: *Is domain-specific inhibitory control necessary to solve problems that are inconsistent with individuals' mathematical associations* and *can domain-specific inhibitory control differentially predict incongruent errors, compared to, and controlling for other cognitive skills?*

Using domain-specific negative priming tasks that examine domain-specific inhibitory control (See chapter 3), I predicted that negative priming effects would emerge. This would suggest that participants held mathematical associations and that successful performance on inconsistent problems requires inhibiting them (Lubin et al., 2016). Further, the proposed model emphasizes that the reason solvers may make incongruent errors is because of failure to inhibit their associations. Therefore, I predicted that domain-specific inhibitory control would positively correlate with, and predict, the number of incongruent errors participants made, controlling for other cognitive functions. While mathematical competency, reading comprehension, and other cognitive skills are important for word problem performance (Bjork & Bowyer-Crane, 2013; Daroczy et al., 2015), I predicted they would not be significant predictors for incongruent errors. This would suggest that the reason participants were making incongruent errors was because of lack of domain-specific inhibitory control, rather than other cognitive skills, such as reading comprehension.

The ***third aim*** of the present study was to establish dialogue with individuals to further understand their mathematical association beliefs, classroom experiences that may have contributed to them, and their overall understanding and approach to solving word problems. To explore this aim, analyses were conducted on the following research questions: *Do solvers believe in mathematical associations, do prior experiences impact their beliefs,* and *how do solvers understand and approach word problems?*

While the semi-structured interview was mainly exploratory, I predicted some general trends, as well as trends specific to each group. Overall, I predicted that participants would be aware of and believe in these mathematical associations. Based on classroom data (Chapman, 2006; Depaepe et al., 2010) and word problem textbooks (Verschaffel et al., 2000; Xin, 2007), I expected participants to say their associations developed from educational practices and/or recalling that they usually produced the correct answer. As a result, I expected individuals to indicate that the inconsistent problems were the hardest. I predicted that group A would elicit a more narrative-oriented approach to solving problems and emphasize the importance of understanding the relations between characters and objects. Group B would emphasize a more paradigmatic-oriented approach and focus on identifying the mathematical structure. It may be possible that individuals in group B would not recognize that some problems contained inconsistencies due to not inhibiting their mathematical associations and focusing on the mathematical structure.

The foundation of the proposed model originates from the idea that problem solving is a human activity and we must understand how prior experiences influence one's problem-solving process. Supporting the model, I predicted individuals' prior experiences would influence why they use their mathematical associations.

Chapter 2: Literature Review

Educational practitioners and researchers alike have stressed the importance of connecting mathematical curricula with the real world (Gainsburg, 2008). Word problems are arguably teachers' most powerful tool in doing so. Narratives can be interchanged to demonstrate how numerical values can be applied to different practical, or everyday situations. Yet, teachers and textbook writers struggle to: (a) apply real-life situations to their problems, and (b) emphasize the importance of comprehending the narrative (Palm, 2006; Verschaffel et al., 2000). Because of this, individuals often fail to develop the ability to understand the practicality of word problems (Gerofsky, 1996, 2004; Van Dooren et al., 2005). In 2000, the National Assessment of Educational Progress (NAEP) identified that only 61% of 12^{th} grade students believed that mathematics was useful for real-world problem solving, down 10% from the previous decade. Individuals that did believe in the practicality and importance of mathematics exhibited stronger performance compared to those who did not (Braswell et al., 2001). More recent reports omitted survey-based questions. However, the 2019 NAEP report identified that over 40% of the 12^{th} grade sample fell below basic proficiency levels, an increase from previous years. Approximately half of the problems used were word problems (NAEP, 2019).

Lack of emphasis on real-world applications may discourage individuals from fully comprehending the narrative, despite having the proper reading comprehension skills. As a result, students of all ages are prone to: (a) calculate and manipulate all the numerical values present, whether the problem is solvable, all numerical values presented are required to produce an answer, or if the answer is realistic, and (b) use suboptimal strategies to identify the mathematical operation (Inoue, 2005; Jiménez & Verschaffel, 2013). For example, in the popular "bus problem" from Silver et al. (1993): "The Clearview little league is going to a Pirates game.

There are 540 people including players, coaches, and parents. They will travel by bus, and each bus holds 40 people. How many buses will they need to get to the game?" Mathematical procedure dictates that you divide 40 from 540 to produce an answer of 12.5 buses. However, conventional wisdom (and the correct answer) dictates you cannot have half a bus and must round up to 13. Numerous studies have designed similar problems and revealed that individuals of all ages mainly consider mathematical procedure for calculations rather than thinking about the practicality of their answer, suggesting the separation between real-life and mathematics when solving word problems (DeWolf et al., 2014; Greer, 1993; Inoue, 2005).

Neglecting real-life applications have downstream effects on teachers' lessons, the word problems used in classrooms and textbooks, and the strategies that students use (Depaepe et al., 2014; Khoshaim, 2020). As previously mentioned, word problems are mathematical problems. The performance-based outcome of word problems is to produce an answer, not to necessarily understand the linguistic narrative or connect the problem to real-life situations. However, when teachers and students are focused on the numerical answer and not the narrative, empirical evidence suggests superficial teaching strategies emerge (Brunner et al., 2010; Rosales et al., 2012). This can result in the use of mathematical associations and suboptimal performance (Verschaffel et al., 2020).

The proposed inhibitory performance-based model from chapter 1 highlights that to be a successful problem solver, you must inhibit: (a) the notion that all numerical values presented in a problem are needed to produce the answer, and (b) the cognitive associations between specific words and mathematical operations. The following sections examine the implications of neglecting real-life applications with regards to lessons, word problems, and strategies, and how this influences an individual's mathematical association beliefs.

Numerical Value Associations

Many times, word problems contain all the information the solver needs for successful solving. However, real-world word problems can often involve vague conditions that cannot be solved by applying mathematical operations to the numerical values presented (Verschaffel et al., 2020). For example, in the problem, "John's car can reach a maximum speed of 120 miles per hour. If John drives for 15 hours straight, how far will he have driven?" The problem is unsolvable with the current information as John will not be able to obtain the maximum speed for 15 hours straight (e.g., traffic, refill the car with gas, bathroom breaks, etc.). This ambiguity in word problems has allowed researchers to categorize problems into two categories based on if real-world knowledge is required for a proper conceptual understanding.

Problematic word problems, or P-items, reflect real-world scenarios and require the application of real-world knowledge for a proper conceptual understanding (Verschaffel et al., 1994, 2010, 2020). These problems cannot simply be solved by applying an operation to the numerical data presented (Dewolf et al., 2013). P-items often contain irrelevant numerical information and/or are unsolvable with the given information. Standard problems, or S-items, can be solved using the more apparent mathematical operation and use all the numerical values presented. S-items are more common in school curricula and follow the didactical contract of arithmetic problems: (a) all problems are solvable with one answer, (b) all numerical values must be used to produce an answer, and (c) some manipulation(s) must occur (Jiménez, 2012; Reusser & Stebler, 1997).

P-items and S-items may require different strategic approaches for successful solving. Theoretical frameworks for S-items have predominantly focused on the computational aspect of identifying the mathematical operation and producing an answer (e.g., Hegarty et al., 1995).

Mathematical modeling for P-items involves understanding both the problem, and the produced answer, within its situational context (Verschaffel et al., 2002). Blum and Niss (1991) proposed that once an individual produces an answer, they must interpret if the outcome is appropriate or reasonable based on the word problem narrative. For example, in the problem "Steve bought 4 planks of 2.5 meters each. How many planks of 1 meter can he saw out of these planks?", one cannot simply use all numerical values present to produce an answer (Bernardo & Calleja, 2005; Verschaffel et al., 1994). A successful solver would identify that the seemingly correct response of 10 is not an appropriate answer; only two 1 meter planks can be cut from each original plank. They would then need to update their response accordingly.

Each item plays a different role in improving an individual's mathematical reasoning and computational skills (Kaiser, 2017). However, associating the didactical contract of arithmetic problems to all word problems (both P-items and S-items) has allowed students to "treat (word problems) as an artificial, puzzle-like task that has to be solved by identifying and executing the mathematical operation that is ''hidden'' in the problem" (DeWolf et al., 2014, pg. 148). Empirical work has identified that teacher beliefs, classroom climates, and the word problems implemented in classrooms have promoted the cognitive association between arithmetic problem rules and word problems (Gravemeijer, 1997; Verschaffel et al., 2010).

Numerical Associations and Classrooms

A student's understanding of P-items and S-items are directly influenced by the quality and type of classroom instruction (De Corte et al., 2008). Two approaches to word problem lessons have been identified in observational-based research (Chapman, 2006). Paradigmatic-oriented approaches focus on the mathematical structure of the problem, which are predominantly context-free. In contrast, narrative-oriented approaches focus on the context, or storyline of the problem, which help solvers understand the narrative and the relationship between characters and objects (See for review, Chapman, 2006). While they are not mutually exclusive, examination of teaching approaches identified the former has played a more prominent role in classrooms (Chapman, 2006; Depaepe et al., 2009, 2014). In examining P-items, Cramer et al. (1993) identified that most elementary school teachers immediately set up an equivalent numerical equation to solve rather than questioning the authenticity of the problem, examining if there was irrelevant numerical information, or explaining the narrative to their students. Similarly, in a seven-month long observational study of two middle school teachers, Depaepe et al. (2010) identified that common themes from lessons were more frequently oriented to a paradigmatic approach. Using a coding scheme for each word problem discussed in class, over 60% of problems talked-through identified the components of the mathematical structure, independent of how they related to the situational narrative. Less than 4% discussed the real-life applications of the problem and less than 5% interpreted if the answer was appropriate within the situational context of the problem.

Based on the problems presented in classrooms, Sánchez-Barbero et al. (2020) proposed teachers internalize that all numerical values presented must be used to produce an answer. When encountering P-items, where conceptual understanding of the narrative is essential for successful performance, Inoue (2005) suggests that teachers' beliefs may influence how they interpret the situational narrative. For example, Kiliç's, (2017) interviews with pre-service teachers revealed that some teachers erroneously adjusted their understanding of the P-item's narrative so all numerical values could be used to produce an answer. This can result in teachers failing to emphasize how the narrative relates to the computational steps. In lessons focused on P-items, Rosales et al. (2012) identified that 11 third to fifth grade teachers (students ranged from 8- to 11-years-old) were still predominantly using paradigmatic-oriented approaches. One example identified a teacher explaining why a specific calculation occurred, but their reasoning was erroneous from the actual word problem narrative. Other examples showed that even when teachers recognized a student's mathematical procedure was inconsistent with the situational narrative, they encouraged them to continue with their calculations when they still produced the correct answer.

Türker and colleagues (2010) suggest that teachers' emphasis of paradigmatic-oriented lessons can also result from them not having the proper mathematical modeling skills to thoroughly navigate the situational narrative or understand real-life applications. At times, mathematics teachers have experienced difficulties solving the same P-items that they would give their students (Depaepe et al., 2014; Verschaffel et al., 2020). As a result, curricula have focused on S-items. In cases where P-items are present in the classroom, many teachers still treat them as S-items and follow the didactical contract of arithmetic problems (Sánchez-Barbero et al., 2020; Silver et al., 2005). To date, only one study has directly examined how teachers grade responses to P-items; Verschaffel et al. (1997) identified that future elementary school teachers gave higher performance scores to the unrealistic mathematical answers that followed the didactical contract rules than to more realistic answers when evaluating possible responses produced by the researchers.

Numerical Associations and Textbook Problems

The lack of real-life problems are also demonstrated in mathematical textbooks. While there is limited data on textbook problem type, Verschaffel et al.'s (2010) analysis of textbook studies revealed that most problems produce one answer and include no irrelevant information, whether extraneous numerical values or superfluous dialogue. Other studies have shown that textbook problems lack variety regarding the strategic approaches needed for successful solving. Olkun et al.'s (2002) examination of textbooks identified that all problems were S-items. Further, a vast majority of word problems were "result unknown" problems (e.g., John has 5 apples. He gave 3 apples to Mary. How many apples does John have now?) compared to "change unknown" or "initial unknown" (e.g., John has some apples. He gave 5 apples to Mary and now he has 9 apples. How many apples did John start with?; Peterson et al., 1989), thus allowing students to process and manipulate all numerical values in the order they appear (Vondrová et al., 2018). Olkun et al. (2002), and Xin (2007) demonstrated that students performed worse on problems that were underrepresented in mathematical textbooks.

Numerical Association Implications

The previous sections argue that lessons and textbook problems may influence how students decipher which numerical values are needed to produce the correct answer. Rather than understanding how the situational narrative relates to computational processing steps, individuals learn to use the didactical contract of arithmetic problems and include all numerical values in their equivalent numerical equation (Jiménez, 2012; Verschaffel et al., 2020). While empirical work has been limited and has predominantly focused on children and adolescents that still may be developing their mathematical modeling skills (e.g., Kaiser, 2020), the results support the notion of associating arithmetic problem rules with word problems. For example, studies have identified that embedded irrelevant linguistic information had minimal effect on students' word problem performance (Englert et al., 1987; Ng et al., 2017; Vondrová et al., 2018). However, irrelevant numerical information can significantly impact performance (Jiménez & Verschaffel, 2013; Ng et al., 2017; Verschaffel et al., 1999).

Jiménez and Verschaffel (2013) emphasized that there are four different types of P-items, or non-standard problems, that violate the didactical contract of arithmetic problems: (a) unsolvable problems, (e.g., John has 20 dollars. Mary gave John 13 dollars so he could buy a ticket to the baseball game. How much money does Mary have now?), (b) multiple solution problems (e.g., John has a bag that contains 20 marbles. Some of the marbles are blue. The next day, he went to the store and bought 6 blue marbles. How many blue marbles does John have now?), (c) given solution problems (e.g., John made 25 cupcakes for the school bake sale. Mary also decided to help out and made 15 cookies. How many cupcakes are there at the bake sale?), and (d) irrelevant data problems (e.g., Mary had 22 seashells in her collection. Mary went to the beach and found 8 seashells and 6 rocks. How many seashells does she have now?). Regardless of the problem type, their results demonstrated that students in first through sixth grade exhibited difficulty on all problems that violate the didactical contract. Similar results have been found in other non-standard word problem studies (e.g., Littlefield & Rieser, 1993; Ng et al., 2017). Jiménez and Verschaffel (2013) argue that solvers approach word problems with the expectation that they will be given S-items. Therefore, the failure to dissociate these beliefs with word problems has resulted in individuals not being aware when irrelevant numerical information is present (Jiménez & Ramos, 2011; Ng et al., 2017). Solvers may need to inhibit their numerical association in order to understand the situational narrative and to determine which numerical values are relevant.

Operational Associations

Simple arithmetic word problems that involve one-step calculations represent the first word problems children experience. One of the most common problem structures is Compare problems (e.g., "John has 13 apples. Mary has 3 less apples than John. How many apples does

Mary have?"), which compare the numerical values between two or more sets (Riley et al., 1984). This type of problem has given individuals significant difficulty due to the static relationship between variables and the inclusion of relational terminology (e.g., more, less, altogether, fewer; Hegarty et al., 1992, 1995; Riley & Greeno, 1988; Schumacher & Fuchs, 2012).

Relational terminology may directly transform to a mathematical operation. However, its relation to the characters and objects determines the operational direction (e.g., either addition or subtraction; Pape, 2003). Empirical work has identified that individuals associate relational terminology to different mathematical operations (e.g., "more" and addition, "less" and subtraction; Hegarty et al., 1995; Stern, 1993; Warren, 2006), which can significantly impact performance (Boonen et al., 2016; Hegarty et al., 1992; Pape, 2003). Different constructs have been proposed as to why individuals use these associations in word problem solving, despite the inaccuracies they produce. Boonen and colleagues' (2013) word problem model suggests that successful problem solvers must produce visual-schematic representations of the narrative and possess relational processing skills, which represent deciphering the relations between relational terminology, characters, and objects. Relational processing is directly influenced by an individual's reading comprehension skills (Lee et al., 2004). This suggests that individuals with poorer reading comprehension skills are more likely to use these operational associations as they do not have the skills to develop more accurate mental representations of the problem (van der Schoot et al., 2009). Boonen et al.'s (2013) path analysis of sixth grade students revealed significant relations between reading comprehension skills and relational processing skills. Further, relational processing skills mediated the relationship between reading comprehension and word problem performance. As relational terminology problems become linguistically more complex, individuals may exhibit difficulties processing the situational narrative and be more likely to rely on their operational associations, thus emphasizing the importance of reading comprehension skills (Boonen et al., 2016; Pongsakdi et al., 2019; Vilenius-Tuohimaa et al., 2008).

As individuals develop appropriate reading comprehension skills, empirical work has suggested that individuals may still continue to use their associations, as they have previously been successful (Jaffe & Bolger, 2023; Verschaffel et al., 2010). As a result, other theories explaining the prevalence of using operational associations in word problem solving have focused on strategic approach deficits, rather than comprehension deficits. The keyword method, a popular classroom strategy, promotes students to analyze individual statements in a word problem, mentally highlight the keyword(s) they believe represents the mathematical operation, and directly translate the information to a numerical equation (Briar & Larkin, 1984). This strategy allows individuals to use fewer cognitive resources by neglecting the situational context but is more prone to translational errors (Campbell et al., 2007; Verschaffel et al., 2020). Using eye tracking methods, results from Hegarty et al. (1995) identified that undergraduate students who used the keyword method displayed more inaccuracies. Unsuccessful problem solvers spent more time fixating on the numerical values and relational terminology compared to the successful problem solvers who spent more time focusing on the situational narrative. Other studies have shown that individuals of all ages perform significantly worse on problems where the relational terminology is inconsistent with the perceived operation (e.g., “more” in a subtraction problem), compared to problems where the relational terminology is consistent with the perceived operation (Lewis & Mayer, 1987; Pape, 2003; Verschaffel, 1994). Kelly et al.'s (2003) results with an undergraduate population indicated that reading comprehension skills did not affect the frequency of reversal errors (i.e., using the wrong operation), demonstrating the usage of inefficient word problem strategies being the main limitation.

Reading comprehension and strategic deficits may influence how an individual associates relational terminology to mathematical operations when solving problems. Kintsch and Greeno's (1985) arithmetic word problem model and the proposed inhibitory performance-based model emphasize the importance of reading comprehension skills and constructing set schemas (Greeno, 1988). Associating relational terminology with mathematical operations allows individuals to produce a (suboptimal) mathematical model without needing to comprehend, or appropriately identify, the relationship(s) between characters and objects (Hegarty et al., 1992). However, comprehension and strategic frameworks fail to consider how or where individuals form operational associations, and why associations persist despite sufficient evidence stating they may be detrimental to performance. Like the didactical contract of arithmetic problems, lessons and word problems (either implicitly or explicitly) are promoting the cognitive associations between word and operation, thus allowing individuals to neglect the situational narrative and still be successful (Orrantia et al., 2005; Seifi et al., 2012). The following sections further demonstrate how neglecting the narrative, or real-life applications, in mathematics curricula can further promote operational associations.

Formation of Operational Associations

An individual's first experience with numerical values and mathematical terminology does not begin with formal education. Their home environment plays a crucial role in their mathematical learning (Ramani & Siegler, 2014) and is where many individuals are introduced to relational terminology (Eason et al., 2022). Discourse studies measuring interactions between parents and children revealed the home is where children develop their understanding of how relational terminology can relate to changes in numerical sets (Walkerdine & Lucey, 1989; Walkerdine, 1990). For example, “more” was commonly used during meal time to represent either a desire to add more food to their plate, or the parent asking the child if they wanted more to eat. Further, a child’s development on the ordinal relations between numerical values and understanding of magnitudes were valuable tools to learning the associations between relational terminology and numerical values (Fuson, 2013; Leyva et al., 2021; Purpura & Lonigan, 2013). Home practices can significantly influence mathematical and word problem success as individuals take knowledge from their home environment and apply it to their formal education (e.g., Ece Demir-Lira et al., 2019; Elliott & Bachman, 2017). Subsequently, individuals may implicitly form the cognitive associations between relational terminology and mathematical operations prior to their exposure to formal word problem lessons and use this knowledge in the classroom.

Operational Associations and Classrooms

The “numerical association” section emphasized the different teaching approaches to word problem solving: paradigmatic-oriented and narrative-oriented (Chapman, 2006). Successful identification of the mathematical operation may be accomplished by both approaches depending on the problem type. For P-items, the operation may not be as easily identifiable compared to S-items (Verschaffel et al., 2020). Therefore, successful solvers must fully understand the situational narrative and the relations between both characters and objects (Cummins, 1991). Chapman (2006) identified that some teachers emphasized that the situational context is essential to successful solving and encouraged students to have an accurate mental representation prior to performing mathematical calculations. However, Depaepe and colleagues’ (2014) chapter on teachers’ beliefs and approaches to problem solving revealed a consistent theme: neglecting the narrative has encouraged suboptimal approaches to identifying the mathematical operation.

Data selection has been a popular construct in paradigmatic-oriented approaches. Rather than identifying the relations between characters and objects, teachers encourage students to isolate information they believe is relevant for identifying the operation (Depaepe et al., 2014; Rosales et al., 2012). Jiang et al.'s (2020) results suggest that teachers have their own heuristic biases and difficulties inhibiting associations. Therefore, teachers may have a strong tendency to incorporate their operational associations within the classroom. For example, many classrooms have keyword posters to help students learn the associations between words and operations (Powell et al., 2022). Capraro and Joffrion (2006) showed that some teachers even held lessons demonstrating that relational terminology words represent different operations and encouraged students to not spend time trying to comprehend the problem. While other examples show teachers not explicitly stating that a specific relational word equated to a specific operation, they still promoted a one-to-one correlation between word and operation (e.g., keyword method; Pennequin et al., 2010; Rosales et al., 2012). These approaches have shown to be detrimental for solving relational terminology P-items as the operation is generally inconsistent with an individual's perceived association (Verschaffel et al., 2020). However, students can use their operational associations on S-items and routinely be successful.

Operational Associations and Textbook Problems

Classroom lessons are influenced by the word problems presented in textbooks (Csíkos & Szitányi, 2019). Likewise, students form problem-solving strategies based on teaching approaches and their exposure to different problem types (Carter & Norwood, 1997; Gravemeijer, 1997; Hadar, 2017; Pongsakdi et al., 2016b). Analysis of textbook problems revealed that a vast majority of relational terminology problems coincide with an individual's associations (Orrantia et al., 2005; Verschaffel et al., 2000; Xin, 2007). Verschaffel and colleagues' (2000) analysis identified that over 90% of textbook problems could be correctly solved using the keyword method. Similarly, Xin's (2007) analysis of U.S. and Chinese textbooks revealed that U.S. textbooks presented an unbalanced presentation of relational terminology word problems. While significantly more problems contained consistent language in U.S. textbooks, the Chinese textbooks were more evenly balanced between consistent and inconsistent relational terminology problems. Examining word problem performance for individuals that used their respective textbooks, U.S. middle school students demonstrated significant struggles on inconsistent problems compared to their Chinese middle school counterparts (Xin, 2007).

The lack of variety in textbook problems is not unique to U.S. textbooks. Similar patterns have been identified in Spanish (Orrantia et al., 2005), Finnish, Thai (Pongsakdi et al., 2006a), and Greek textbooks (Gkoris et al., 2013). The goal of textbook problems is to promote mathematical modeling and critical thinking skills (Verschaffel et al., 2020). In fact, some mathematical curricula have modified their textbooks to promote this type of thinking (e.g., Scheon et al., 2021). However, many textbooks still allow individuals to be successful by using their cognitive associations between relational terminology and mathematical operations. This prevents learners from suppressing a suboptimal cognitive approach and understanding the situational context (Verschaffel et al., 2020).

Operational Association Implications

The associations between relational terminology and mathematical operations develop prior to formal education (Walkerdine & Lucey, 1989; Walkerdine, 1990). Teaching practices and textbook problems have promoted individuals to use their associations in their problem solving (Powell et al., 2022; Verschaffel et al., 2020). While research has been scarce, empirical work has suggested that individuals as young as 9-years-old have already formed strong associations between relational terminology and mathematical operations (Lubin et al., 2013). In negative priming tasks, children demonstrated difficulty solving consistent operational association problems that immediately followed inconsistent operational association problems, compared to consistent operational association problems that followed problems that had no conflict with operational associations (Lubin et al., 2013; Shum & Chan, 2020). The negative priming effects that emerged suggest that individuals hold operational associations, use prior experiences to solve problems, and operational inhibitory control is needed for successful problem solving. Similar patterns have been shown in adults as well (Lubin et al., 2016).

The keyword method has been an area of interest for word problem research and numerous studies have focused on the strategic approaches used by individuals of all ages (e.g., Hegarty et al., 1995; Lewis & Mayer, 1987; Pape, 2003). However, these studies fail to consider why or how individuals develop operational associations and why they are commonly used. Theoretically, using the keyword method should only produce the correct answer 50% of the time on one-step word problems. However, as shown in the previous section, it can lead to over 90% accuracy (Verschaffel et al., 2000). Inhibitory control work on mathematical reasoning has shown that individuals can demonstrate difficulties inhibiting inefficient strategies that have previously produced correct answers (Khng & Lee, 2009). The empirical evidence alludes that instructional practices and textbook problems further cement the associations between relational terminology and mathematical operations and that domain-specific inhibitory control is needed for successful performance (Shum & Chan, 2020; Verschaffel et al., 2020).

Overall Discussion

Individuals must possess appropriate reading comprehension skills to understand the situational narrative (Vilenius-Tuohimaa et al., 2008), a proper strategic approach to identify semantic relations and to transform the word problem into an equivalent numerical problem (Hegarty et al., 1995), and appropriate mathematical computational skills to subsequently solve the problem (Daroczy et al., 2015; Kintsch & Greeno, 1985). While it may be expected that individuals already possess sufficient comprehension and mathematics skills prior to word problem instruction, classroom lessons help students develop strategies to solve word problems (Chapman, 2007; Depaepe et al., 2014; Greer, 1997).

Neglecting the real-life applications of word problems has allowed instructional lessons to predominantly focus on the mathematical procedure and encourage suboptimal strategies to identify the numerical values and mathematical operation (Depaepe et al., 2014; Panaoura et al., 2009; Verschaffel et al., 2010). This can inhibit students from constructing accurate mathematical models and understanding the relations between characters and objects (Gerofsky, 2009). For example, Seifi et al.'s (2012) interviews with middle school mathematics teachers revealed that incoming students predominantly used their mathematical associations to solve word problems. The students had very little understanding of how to comprehend the situational narrative as their prior classroom experiences had promoted the use of mathematical associations.

The mathematical associations emphasized in the proposed inhibitory performance-based model and throughout this chapter do not develop from word problem practices. The notion that: (a) all problems are solvable with one answer, (b) all numerical values must be used to produce an answer, and (c) some manipulation(s) must occur, originated from the didactical contract of arithmetic problems (Jiménez, 2012; Reusser & Stebler, 1997). Likewise, the associations between relational terminology and mathematical operations may develop from an individual's home environment (Walkerdine & Lucey, 1989; Walkerdine, 1990). Practices and textbook problems have promoted these ideas in curricula and have encouraged students to use their mathematical associations when navigating word problems. Therefore, it has been suggested that in order to produce the correct answer on inconsistent operational and numerical problems, individuals must inhibit their mathematical associations (Jaffe & Bolger, 2023).

Chapter 3: The Present Study

Chapters 1 and 2 illustrate the mathematical word problem solving process and how mathematical associations develop and are reinforced through lessons and textbooks. Verschaffel et al. (2010) argue that individuals gradually develop problem-solving strategies based on the problem types they experience. As individuals predominately experience S-item problems and can use their mathematical associations to produce correct answers, Khng and Lee (2009) suggest that solvers may struggle to inhibit their mathematical associations and utilize a more appropriate strategy. While domain-specific inhibitory control may play a significant role in mathematical word problem solving (e.g., Passolunghi & Pazzaglia, 2005; Passolunghi & Siegel, 2001), Verschaffel et al. (2020) and Van Dooren and Inglis (2015) attest that word problem research has yet to fully examine the relations between inhibitory control and word problem performance. For instance, Verschaffel et al.'s (2020) analysis of word problem studies revealed that inhibitory control has been used to explain suboptimal performance on relational terminology problems and non-standard word problems, yet they were not aware of any studies that directly examined the relationship. Similarly, other studies have used domain-general inhibitory control tasks, like the color Stroop task (Agostino et al., 2010; Passolunghi et al., 2022) or numerical Stroop task (Lee et al., 2009), to understand the relations between inhibitory control regarding mathematical associations and word problem performance. However, educational research has shown that tasks that test for domain-general cognitive skills (e.g., color Stroop task) may not be an appropriate measure for domain-specific skills (e.g., inhibiting mathematical associations; Cragg & Gilmore, 2014; Wilkinson et al., 2019).

To further understand the relations between domain-specific inhibitory control and word problem performance, word problem research must use paradigms that can reveal how mathematical associations impact problem solvers. For example, Jiménez and Verschaffel (2013) acknowledge that while their non-standard word problem data suggest that students have difficulties with problems that violate the didactical contract of arithmetic problems, structured interviews could give insight to how their mathematical associations influenced their problem-solving process. Similarly, domain-specific inhibitory control tasks, like a negative priming task, can help uncover this relationship. However, I only found three studies (Lubin et al., 2013, 2016; Shum & Chan, 2020) that used negative priming paradigms on relational terminology problems and no studies that included domain-specific inhibitory control tasks on non-standard problems. No studies to my knowledge have included structured interviews regarding mathematical associations or a think-out-loud protocol on P-items to further investigate how solvers process these types of word problems.

Overall, the classroom evidence provided in chapter 2 points to domain-specific inhibitory control being a significant factor in word problem performance. However, the lack of explicit evidence has halted the integration of inhibitory control information into classrooms (Van Dooren & Inglis, 2015). If inhibitory control work can parallel the results of other executive function work, there may be significant classroom implications (Fuchs et al., 2019). Through working memory tasks, empirical evidence has shown that working memory is a significant predictor to word problem success (Lee et al., 2004, 2009; Swanson, 2006). This has resulted in schema-based interventions (e.g., Flores et al., 2016; Fuchs et al., 2021; Schumacher & Fuchs, 2012) and other cognitive strategy training lessons (e.g., Swanson, 2014) to help reduce the cognitive workload, and help solvers identify the structure and mathematical operation. Jaffe and Bolger’s (2023) literature review on the relationship between working memory and word problem success suggests that working memory capacity may impact how solvers process all facets of the linguistic component. Understanding that inaccuracies may not be due to numerical or linguistic incompetence, but to limits in their information-processing ability (e.g., Fuchs et al., 2019; Kintsch & Greeno, 1985), may be assets to helping teachers design lessons (Jaffe & Bolger, 2023). To understand how word problem lessons and textbooks can influence one's mathematical associations, there must first be a better understanding of the relations between domain-specific inhibitory control and word problem success.

Methods

A total of 108 participants were recruited to participate in this study. Participants were recruited through either undergraduate human development courses at the University of Maryland or from flyers posted around the university. Participation in this study was voluntary and all participants were rewarded with either course extra credit or financial compensation, respectively. Of the original sample, three participants were excluded from analysis due to either not finishing the study or randomly guessing on the word problem section. Overall, 105 participants (*Mage* = 19.16, *SD* = 1.37; 77 Female) were included for analysis. Demographics were self-reported as 55% White, 20% Asian, 7% Hispanic, 7% Black/African-American, 2% Middle Eastern, and 10% as multiple racial identities.

The sample size was determined by conducting two *a priori* power analyses using G*Power (e.g., Erdfelder et al., 1996). Both the ANOVA and regression model analyses suggested that to detect a medium effect size, a minimum of 80 participants would be needed to test the hypotheses. A medium effect size was used as it is consistent with other word problem research (e.g., Jitendra et al., 2007; Walkington et al., 2019). An *a priori* power analysis could not be conducted for the cluster analysis, as it is an *a posteriori* analysis and there is no conclusive way to predetermine how many distinct subgroups would emerge from the sample.

Procedure

Prior to data collection, the study was approved by the Institutional Review Board at the University of Maryland College Park. All participants gave informed written consent prior to participating in the study. Data collection took place in person at the University of Maryland's Benjamin Building and the current study consisted of four sections: (a) cognitive tests, (b) word problems, (c) domain-specific inhibitory control, and (d) semi-structured interview.

Cognitive Tests. Numerical competence (e.g., Daroczy et al., 2015), reading comprehension (e.g., Bjork & Bowyer-Crane, 2013; Vilenius-Tuohimaa et al., 2008), working memory (e.g., Lee et al., 2009), fluid reasoning (e.g., Strohmaier et al., 2021), and inhibitory control (e.g., Lubin et al., 2016) have all positively correlated with word problem success. Therefore, to evaluate these cognitive skills, participants completed subtests from the Woodcock Johnson IV as well as a color word Stroop task. Two subtests were administered from the Test of Achievements (Reading Fluency and Math Facts Fluency) and two subtests from the Test of Cognitive Abilities (Numbers Reversed and Numerical Reasoning).

Reading Fluency evaluates reading comprehension skills, Math Fact Fluency evaluates numerical competency, or arithmetic skills, Numbers Reversed evaluates working memory, Numerical Reasoning evaluates fluid reasoning, and the color word Stroop task evaluates domain-general inhibitory control (See appendix S1 for a concise overview and scoring rubric of each task). All subtests that require being read aloud were played from the official Woodcock Johnson IV recording. The remaining subtests were administered on paper and the color word Stroop task was administered online. Evaluating cognitive skills helps in understanding participants' cognitive profiles, how various skills relate to word problem performance, and the overall relationship between domain-specific inhibitory control and the production of incongruent errors, controlling for other cognitive skills.

Word Problems. Following the “cognitive tests” section, participants completed word problems on Qualtrics XM survey software (Qualtrics, Provo, UT). This section consisted of 75 word problems categorized into five types. The control problem type was “neutral problems” which did not contain relational terminology and all numerical values presented were used and manipulated to produce the correct answer. This was used as a baseline to measure their mathematical word problem abilities. The four other problem types focused on the mathematical associations described in chapters 1 and 2. They include combinations that were either consistent or inconsistent with an individual’s operational association and numerical value association. “Consistent operational association” constitutes a problem where the relational terminology represents the expected mathematical operation (e.g., “more” representing an addition problem) while “inconsistent operational association” constitutes a problem where the relational terminology does not represent the expected mathematical operation (e.g., “more” representing a subtraction problem). Similarly, “consistent numerical association” constitutes a problem where all numerical values are used and manipulated to produce the correct answer while “inconsistent numerical association” constitutes a problem where not all numerical values are used and manipulated to produce the correct answer. The four remaining problem types were defined as: (a) consistent operational association and consistent numerical association (COCN) problems, (b) consistent operational association and inconsistent numerical association (COIN) problems, (c) inconsistent operational association and consistent numerical association (IOCN) problems, and (d) inconsistent operational association and inconsistent numerical association (IOIN) problems. Table 1 provides example problems for each problem type. Each problem type consisted of 15 problems (10 one-step problems and 5 two-step problems) and the problem order was randomized. Problems contained all arithmetic operations. Further, the problems contained a variety of situational narratives, ranging from real-life scenarios to fantasy. All correct responses were single- and double-digit numbers. Participants were instructed that only mental calculations were allowed for problem solving. Both accuracy and response times were recorded.

Table 1

Example word problems

Problem Type	Example Problems
Neutral	John went to the store and bought 46 apples. Later in the day, he saw Mary and gave her 13 apples. How many apples does John have now?
Consistent Operation Consistent Numerical (COCN)	At McDonald's, lunch is \$7. At Wendy's, the same lunch is \$4 more. If you bought 3 lunches at Wendy's, how much would it cost?
Consistent Operation Inconsistent Numerical (COIN)	John went to the store and bought 32 apples for \$2 each. Mary bought 7 less apples than John. However, hers cost \$3 each. How many apples did Mary buy?
Inconsistent Operation Consistent Numerical (IOCN)	At Burger King, lunch is \$12. That is \$3 more than the same lunch at Wendy's. If you bought 2 lunches at Wendy's, how much would it cost?
Inconsistent Operation Inconsistent Numerical (IOIN)	John went to the store and bought 16 oranges for \$3 each. He bought 7 less oranges than Mary. Mary's oranges cost \$2 each. How many oranges did Mary buy?

Think-Out-Loud Problems. Randomly selected participants (n = 52) completed four additional one-step problems (one COCN, COIN, IOCN and IOIN problem) where they verbally expressed their problem-solving process. Recent research has argued that think-out-loud protocols may lead to a more thorough examination of the problem because participants believe they are being closely watched (e.g., Olson et al., 2018). Therefore, accuracy and response time results were not included in analysis. Participants were given instructions to say all of their thoughts out-loud and to solve the problems as they normally would. Participants were given a pen and paper, though they were instructed that they do not have to use it. To help the participants feel more comfortable to speak, the researcher left the room. Participants' expressions were audio recorded, coded, and analyzed.

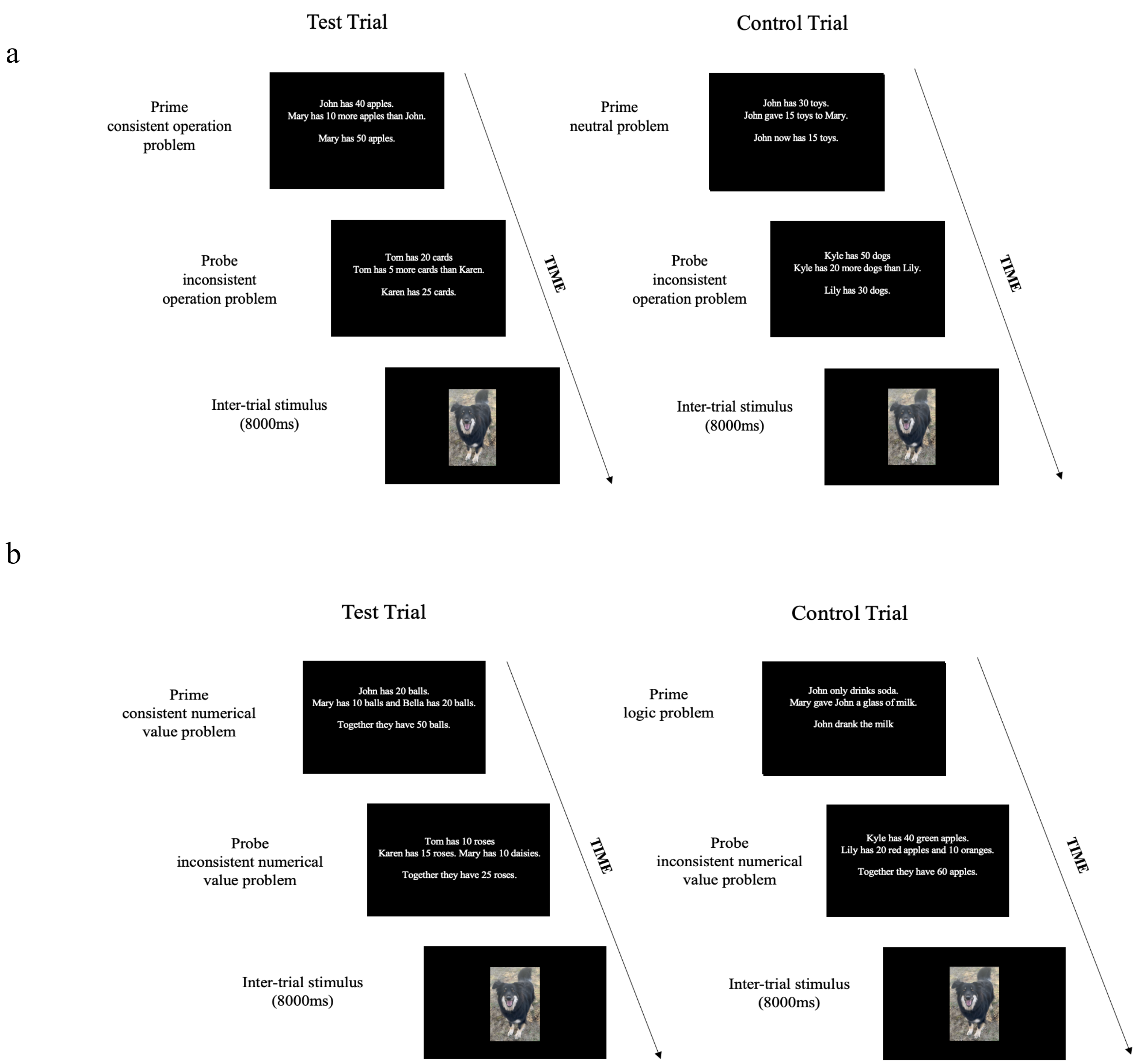
Domain-Specific Inhibitory Control. To evaluate participants' inhibitory control skills regarding mathematical associations, a negative priming task was adapted and modified from Lubin et al. (2013, 2016). The purpose of a negative priming task is to examine if exposure to previous stimuli can influence the response of subsequent stimuli (Tipper, 1985). In this context, would solving a consistent problem influence one's approach to solving a subsequent inconsistent problem, compared to first solving a problem that has no conflict with one's associations, followed by a similar inconsistent problem? If negative priming effects, or performance differences on the inconsistent problems emerge, this suggests that individuals believe in an association and must inhibit it to produce the correct answer (Lubin et al., 2013). This task was completed using PsychoPy software (Peirce, 2007). The goal of this section was to examine inhibitory control rather than calculation skills. Therefore, all problems were one-step, three sentences, required either addition or subtraction, and all numerical values were divisible by five. For these problems, an answer appeared on the screen and participants determined if it was correct or incorrect. Items from the "operational inhibition" task and the "numerical value inhibition" task (see below) were randomized together. Further, the "word problems" section and this section were counterbalanced to account for task interference effects.

Operational Inhibition. Three types of problems were used in this inhibition task: COCN problems, IOCN problems, and neutral problems. Participants completed 16 trial blocks with each trial consisting of two problems. First, participants encountered a word problem (prime item) where they responded either correct (by pressing the "A" key) or incorrect (by pressing the "L" key). Once the response has been recorded, the next word problem (probe item) appeared, and participants responded in the same manner. Half of the problems contained correct answers. Between trials, a graphic appeared on the screen for eight seconds and then advanced to the next trial. Based on previous work, having probe items immediately follow prime items and an eight second delay between trial blocks should be sufficient to reveal any negative priming effects (Lubin et al., 2013; Shum & Chan, 2020; Tipper, 2001). Figure 2 provides an example of the procedure, how the problems were presented on the screen, and example word problems. Eight trial blocks were control trials (neutral problem followed by an IOCN problem) and eight trial blocks were test trials (COCN problem followed by an IOCN problem). Accuracy and response times for both prime items and probe items were recorded.

Numerical Value Inhibition. This task followed a similar procedure to the "operational inhibition" task and contained 16 trial blocks. However, because neutral word problems can technically be classified as "consistent numerical association" problems, the neutral problems in this task were replaced with similar structured logic problems (Figure 2). Therefore, the three types of problems used in this task were logic problems, consistent numerical association (CN) problems, and inconsistent numerical association (IN) problems. No problems in this task contained relational terminology. Eight trial blocks were control trials (logic problem followed by an IN problem) and eight trial blocks were test trials (CN problem followed by an IN problem). Accuracy and response times for both prime items and probe items were recorded.

Figure 2

Sample procedure and example problems for the (a) operational inhibition task and (b) numerical value inhibition task



Semi-Structured Interview. The final section was a semi-structured interview and explored three domains: (a) participants' general understanding and thoughts about word problems, (b) thoughts about the word problems completed in the “word problems” section, and

(c) thoughts and experiences regarding their mathematical associations. This portion of the study was audio recorded and coded for analysis. The interview guide is provided in the appendix (S2).

Analytic Plan

The following analyses were conducted to address the study's research aims.

Research Aim 1: To examine performance on problems that were consistent with mathematical associations compared to inconsistent problems and investigate why participants produced incorrect responses

To address this aim, two within-subjects five-way Analysis of Variances (ANOVAs) were conducted to determine whether there were accuracy and response time differences based on word problem type. Post hoc comparisons using a Bonferroni correction were conducted to examine which problem types elicited the significant differences. Paralleling Jaffe et al.'s (2023) analysis, five chi-square goodness of fit tests (one for each word problem type) were conducted to examine incorrect responses, and whether there were significantly more incorrect responses consistent with participants' mathematical associations (incongruent errors) compared to miscalculation errors. Finally, I conducted a cluster analysis to determine whether there were distinct subpopulations within the sample pool based on accuracy.

Research Aim 2: To investigate how domain-specific inhibitory control relates to word problem performance and the production of incongruent errors

First, analysis focused on the probe items from the "domain-specific inhibitory control" section. Research has demonstrated that negative priming effects are observed when the number of errors and/or response times are greater on test probe items compared to control probe items (e.g., Conway et al., 1999; Lubin et al., 2013; Shum & Chan, 2020). If negative priming effects emerge, this may suggest individuals hold mathematical associations and that they need to be inhibited when solving problems. Participants must correctly answer the prime item to elicit a negative priming effect. Therefore, all incorrectly answered prime item blocks were excluded from analysis. I conducted four paired-sample t-tests (two for "operational inhibition" and two for "numerical value inhibition") to examine if there were accuracy and response time differences between test probe items and control probe items.

To examine the relationship between domain-specific inhibitory control and incongruent errors, while controlling for other cognitive skills, I analyzed data from the "cognitive tests" section, "word problems" section, and "domain-specific inhibitory control" section. The proposed model emphasizes that incongruent errors may be a result of failure to inhibit one's mathematical associations. Further, empirical work has argued that there are different underlying mechanisms behind miscalculation errors and incongruent errors (Martin & Bassok, 2005). Previous research has analyzed incongruent errors independently from miscalculation errors (e.g., Lewis, 1989; Pape, 2003). At times, miscalculation errors have been categorized together with correct responses (e.g., González-Calero et al., 2015), as they both suggest solvers successfully inhibited their associations. For this reason, the following analyses included the number of incongruent errors rather than accuracy on the "word problems" section, as this excludes miscalculation errors.

Performance data from the negative priming tasks were measured by subtracting test probe item accuracy from control probe item accuracy. Higher positive scores represent stronger negative priming effects. For simplicity throughout the rest of the manuscript, the accuracy negative priming effects were classified as "operational inhibitory control" and "numerical inhibitory control," respectively. While response time data may also indicate negative priming effects, I chose to use the accuracy data as I am proposing an inhibitory performance-based model and am interested in the effects of inhibition on accuracy. Further, accuracy effects may suggest participants are failing to inhibit their mathematical associations while response time effects may suggest they need additional time to successfully inhibit their associations.

Bivariate correlations were conducted to examine the relationships between the cognitive skills (reading comprehension, arithmetic, working memory, fluid reasoning, and domain-general inhibitory control), operational inhibitory control, numerical inhibitory control, COIN incongruent errors, IOCN incongruent errors, and IOIN incongruent errors. Only incongruent errors from these problem types were used as these are the only problems that contain inconsistencies. Second, to extract the unique contribution of each cognitive skill with regards to predicting incongruent errors, I conducted three hierarchical regression models. The dependent variables were incongruent errors on COIN problems, IOCN problems, and IOIN problems. The first model for each hierarchical regression had the cognitive skills as the independent variables. Paralleling previous work that examined the relations between domain-general cognitive skills and word problem solving (e.g., Bjork & Bowyer-Crane, 2013; Strohmaier et al., 2021), this model examined how domain-general cognitive skills could predict incongruent errors, when controlling for each other. The second model included both the cognitive skills and the respective domain-specific inhibitory control (i.e., the IOCN model included operational inhibitory control, the COIN model included numerical inhibitory control, and the IOIN model included both operational and numerical inhibitory control). This model added domain-specific inhibitory control to examine if it is a significant predictor of incongruent errors when controlling for cognitive skills and to determine how much more variance a domain-specific variable added to the model.

Research Aim 3: To establish dialogue with individuals to further understand their mathematical association beliefs, classroom experiences that may have contributed to them, and their overall understanding and approach to solving word problems

I chose to add a qualitative analysis component to further understand participants': (a) general understanding of word problems and their overall practicality, (b) thoughts about the word problems in the present study, (c) beliefs and experiences regarding mathematical associations, and (d) approach to solving word problems. I used an *a priori* approach to content analysis. The goal of content analysis is to take large quantities of qualitative data and systematically organize the data into a limited number of meaningful themes (Stemler, 2001). Based on previous teacher-based research (e.g., Chapman, 2006; Moleko, 2021; Pearce et al., 2013; Rosales et al., 2012), I began with two overarching themes: paradigmatic-oriented approaches and narrative-oriented approaches. Based on Depaepe et al.'s (2014) chapter on teachers' beliefs, it is expected that responses to many, if not all, of the interview questions, and the think-out-loud protocol, would either focus on the mathematical structure and be context-free and/or focus on the importance of understanding the situational narrative and the practicality of word problems. For the third component of the interview (beliefs and experiences), I used a binary coding approach as I believed this gave a novel understanding of participants' mathematical association beliefs and their educational experiences.

Exploratory analyses were conducted to determine if the different groups from the cluster analysis elicited different themes from the interview. Comparing two independent proportions tests were conducted to determine if there were significant differences between groups (Andrés & Mato, 1994). Comparing two independent proportions tests were conducted rather than Welsh t-tests as these outcomes were binary (i.e., either paradigmatic and narrative, or yes and no) rather than continuous.

Once the data were collected and transcribed, another researcher and I independently coded the transcripts. After coding every 10 transcripts, we met, compared our coding analysis, worked out any disagreements, and determined if other themes were needed to encapsulate the data. We concluded that both paradigmatic and narrative-oriented were reliable themes for the analyses and other themes were not needed (See appendix S3 for details on coding scheme). Overall, the qualitative data allowed for a more in-depth interpretation of the quantitative results in two ways. First, I was able to extract themes from the overall sample. Second, as distinct groups emerged from the cluster analysis, I was able to examine if groups embodied different themes and how they related to word problem performance.

Chapter 4: Analysis

Analyses were conducted to address the study's research aims.

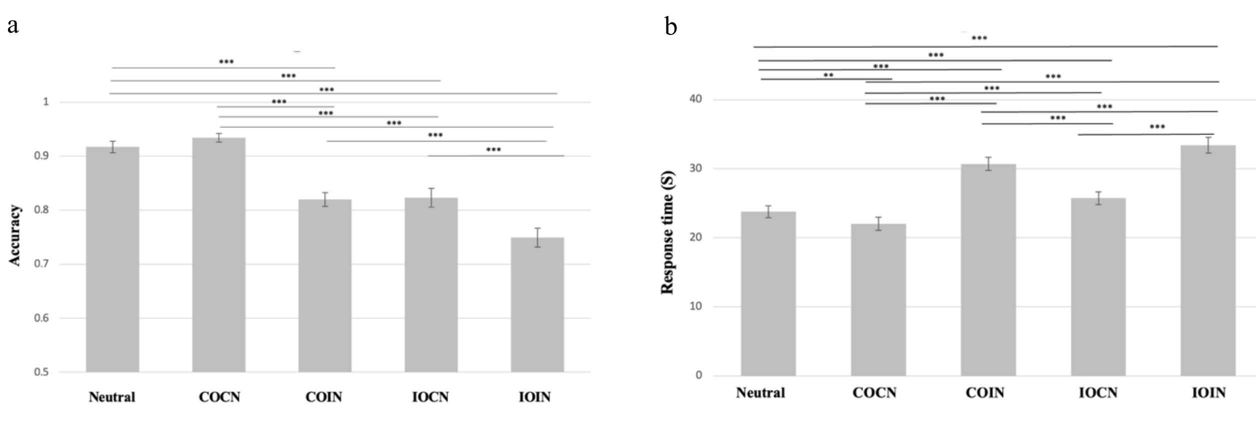
Research Aim 1: To examine performance on problems that were consistent with mathematical associations compared to inconsistent problems and investigate why participants produced incorrect responses

First, a within-subjects five-way ANOVA was conducted to determine whether there were accuracy differences based on word problem type. Comparing accuracy means between neutral problems (M = 0.917, SD = 0.11), COCN problems (M = 0.934, SD = 0.08), COIN problems (M = 0.820, SD = 0.13), IOCN problems (M = 0.823, SD = 0.18), and IOIN problems (M = 0.749, SD = 0.18) revealed significant differences, $F(4,416) = 61.670$, $p < .001$, with $\eta^2 = .372$, suggesting a large effect size (Cohen, 1988; Figure 3a). Post hoc pairwise comparisons with Bonferroni corrections were conducted to determine the significant differences. Participants exhibited significantly higher accuracy on neutral problems compared to COIN ($p < .001$), IOCN ($p < .001$), and IOIN problems ($p < .001$), while there was no significant difference with COCN problems ($p = 1.00$). Participants exhibited significantly higher accuracy on COCN problems compared to COIN ($p < .001$), IOCN ($p < .001$), and IOIN problems ($p < .001$). Participants exhibited significantly higher accuracy on COIN problems compared to IOIN problems ($p < .001$), while there was no significant difference with IOCN problems ($p = 1.00$). Finally, participants exhibited significantly higher accuracy on COIN problems compared to IOIN problems ($p < .001$).

Next, a within-subjects five-way ANOVA was conducted to determine whether there were response time differences based on word problem type. Comparing response time means between neutral problems (M = 23.80, SD = 8.72), COCN problems (M = 22.02, SD = 7.22), COIN problems *(M* = 30.67, *SD* = 9.68), IOCN problems (*M* = 25.72, *SD* = 9.55), and IOIN problems (*M* = 33.42, *SD* = 11.63) revealed significant differences*,* $F(4, 416) = 195.52$, $p < .001$, with $\eta^2 = .649$, suggesting a large effect size (Cohen, 1988; Figure 3b). Post hoc pairwise comparisons with Bonferroni corrections were conducted to determine the significant differences. Participants exhibited significantly faster response times on COCN problems compared to neutral ($p < .01$), COIN ($p < .001$), IOCN ($p < .001$), and IOIN problems ($p < .001$). Participants exhibited significantly faster response times on neutral problems compared to COIN ($p < .001$), IOCN ($p < .001$), and IOIN problems ($p < .001$). Participants exhibited significantly faster response times on IOCN problems compared to COIN ($p < .001$) and IOIN problems ($p < .001$). Finally, participants exhibited significantly faster response times on COIN problems compared to IOIN problems ($p < .001$).

Figure 3

Accuracy (a) and response time (b) results for the word problems section

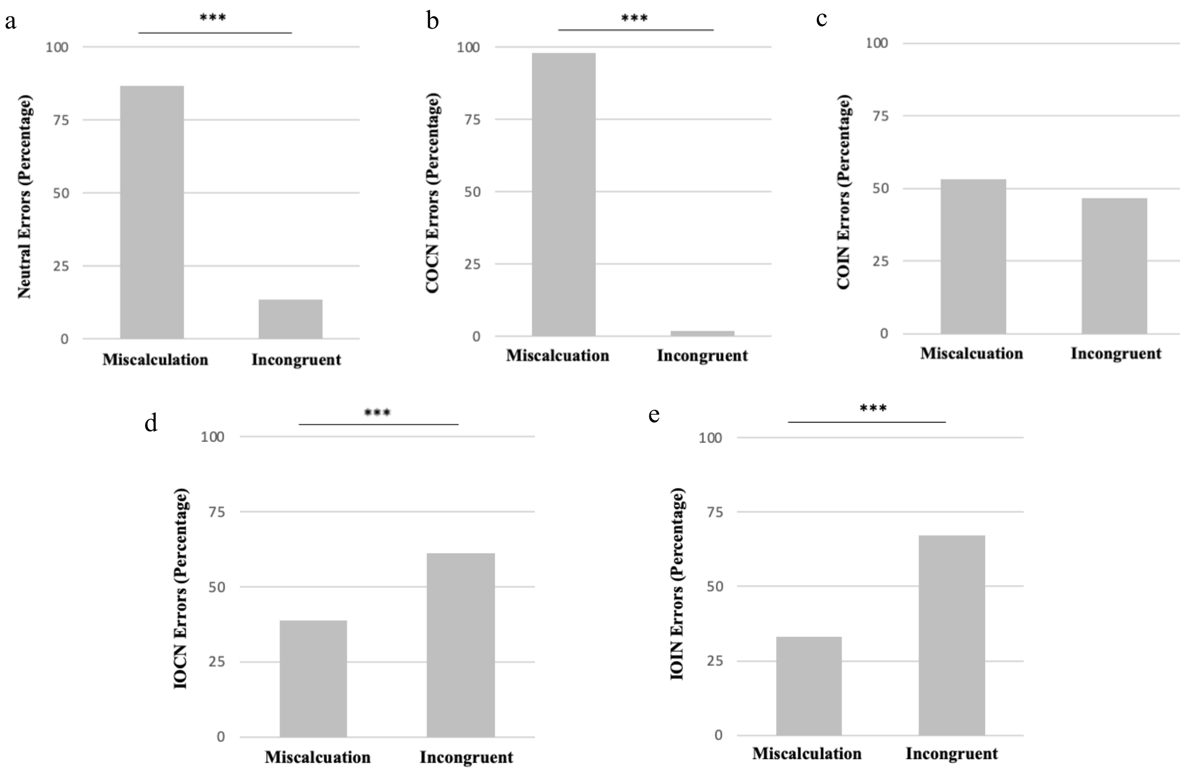


Note. ** indicates $p < .01$, and *** indicates $p < .001$. COCN: consistent operational and consistent numerical association; COIN: consistent operational and inconsistent numerical association; IOCN: inconsistent operational and consistent numerical association; IOIN: inconsistent operational association and inconsistent numerical association.

Next, paralleling Jaffe et al.'s (2023) analysis, chi-square goodness of fit tests were conducted to examine incorrect responses, and whether they were more likely to be incongruent errors or miscalculation errors, for each problem type. For neutral and COCN problems, incongruent errors were classified as using the wrong operation as they only contained features that were consistent with the mathematical associations. For neutral problems, the test indicated that errors did significantly differ by error type, $X^2(1) = 68.10$, $p < .001$, suggesting that participants were significantly more likely to make miscalculation errors than incongruent errors (Figure 4a). For COCN problems, the test indicated that errors did significantly differ by error type, $X^2(1) = 97.15$, $p < .001$, suggesting that participants were significantly more likely to make miscalculation errors than incongruent errors (Figure 4b). For COIN problems, the test indicated that errors did not significantly differ by error type, $X^2(1) = 1.17$, $p = .28$ (Figure 4c). For IOCN problems, the test indicated that errors did significantly differ by error type, $X^2(1) = 13.14$, $p < .001$, suggesting that participants were significantly more likely to make incongruent errors than miscalculation errors (Figure 4d). Lastly, for IOIN problems, the test indicated that errors did significantly differ by error type, $X^2(1) = 44.91$, $p < .001$, suggesting that participants were significantly more likely to make incongruent errors than miscalculation errors (Figure 4e).

Figure 4

Percentage of incongruent errors and miscalculation errors by problem type



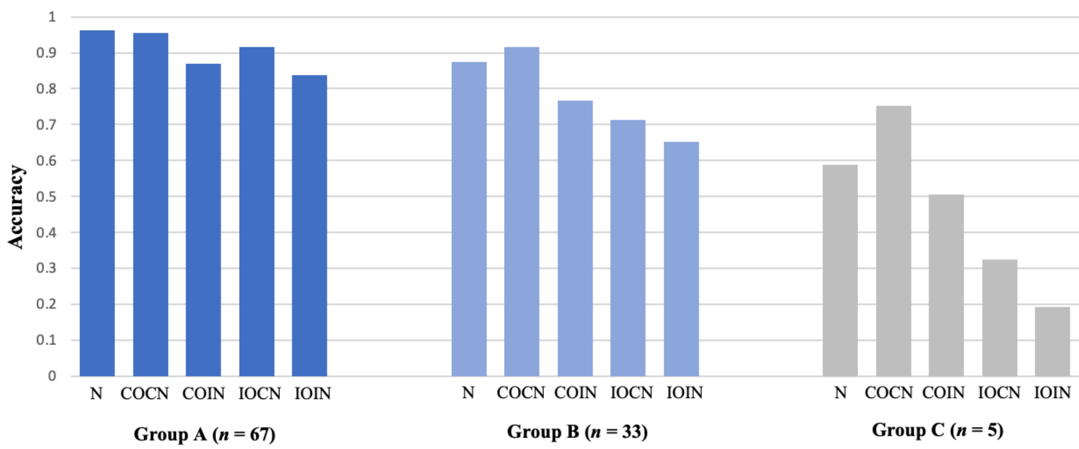
Note. *** Indicates $p < .001$. COCN: consistent operational and consistent numerical association; COIN: consistent operational and inconsistent numerical association; IOCN: inconsistent operational and consistent numerical association; IOIN: inconsistent operational association and inconsistent numerical association.

A cluster analysis was conducted to examine if there were distant subpopulations within the sample pool that support the inhibitory control model from chapter 1. The cluster analysis only included accuracy data as the proposed theoretical model concentrated on correct/incorrect responses, not the time needed to inhibit or complete the problem. First, a hierarchical cluster analysis identified that three subpopulations reliably represented the participant pool. K-means cluster analysis with maximum iterations identified both the sample sizes and means of each cluster as: a) $n = 67$; neutral = 0.962, COCN = 0.956, COIN = 0.870, IOCN = 0.915, and IOIN =

0.839, b) n = 33; neutral = 0.875, COCN = 0.917, COIN = 0.767, IOCN = 0.712, and IOIN = 0.651, and c) n = 5; neutral = 0.588, COCN = 0.752, COIN = 0.505, IOCN = 0.323, and IOIN = 0.191 (Figure 5).

Figure 5

Cluster analysis for the word problem accuracy results



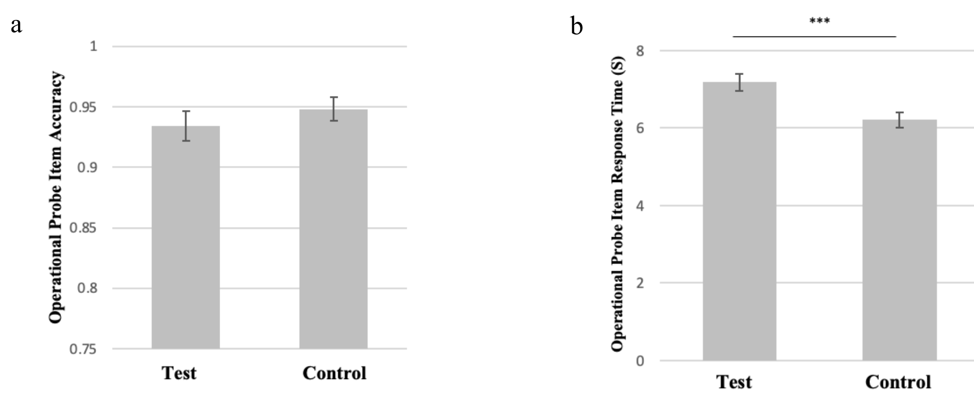
Note. COCN: consistent operational and consistent numerical association; COIN: consistent operational and inconsistent numerical association; IOCN: inconsistent operational and consistent numerical association; IOIN: inconsistent operational association and inconsistent numerical association.

Research Aim 2: **To investigate how domain-specific inhibitory control relates to word problem performance and the production of incongruent errors**

I conducted four paired-sample t-tests (two for "operational inhibition" and two for "numerical value inhibition") to examine if there were accuracy and response time differences between test probe items and control probe items. The accuracy results between the operational inhibition test probe items (M = 0.934, SD = 0.13) and the operational inhibition control probe items (M = 0.950, SD = 0.10) revealed no significant difference, $t(104) = 1.43$, $p = .157$, d =.139 (small effect size; Cohen, 1988; Figure 6a). The response time results identified participants exhibited significantly quicker response times on operational inhibition control probe items *(M* = 6.31, *SD* = 2.09) compared to operational inhibition test probe items (*M* = 7.18, *SD* = 2.27), $t(104) = 6.296$, $p < .001$, $d = .614$ (medium effect size; Cohen 1988), suggesting that negative priming effects emerged, participants held operational associations, and that they must inhibit them for successful problem solving (Figure 6b).

Figure 6

Accuracy (a) and response time (b) results from the operational inhibition task

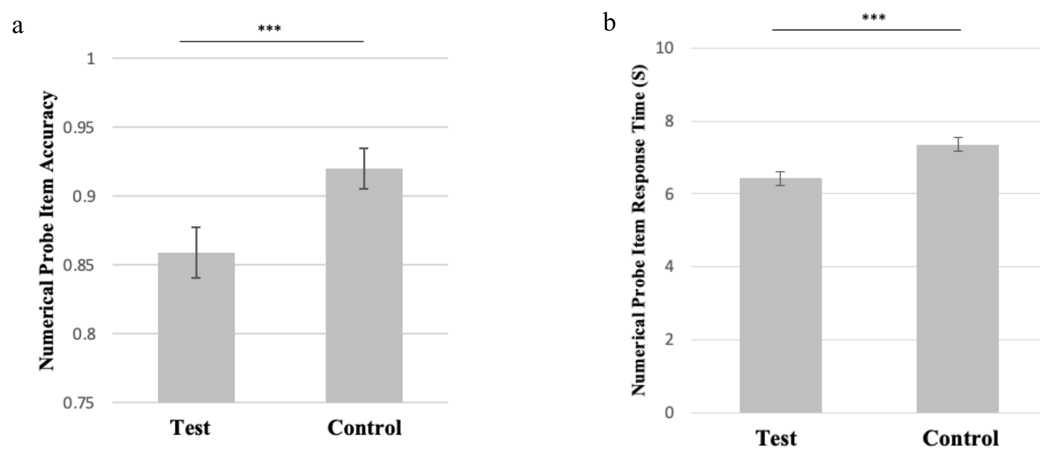


Note. *** Indicates $p < .001$.

The accuracy results for the "numerical value inhibition" task revealed that participants had significantly higher accuracy on the numerical value inhibition control probe items (*M* = 0.924, *SD* = 0.15) compared to the numerical value inhibition test probe items (*M* = 0.859, *SD* = 0.19), $t(104) = 4.828$, $p < .001$, $d = .471$ (medium effect size; Cohen, 1988), suggesting that negative priming effects emerged, participants held numerical value associations, and that they must inhibit them for successful problem solving (Figure 7a). The response time results identified participants exhibited significantly quicker response times on numerical value inhibition test probe items (*M* = 6.42, *SD* = 1.81) compared to numerical value inhibition control probe items (M = 7.35, SD = 1.95), $t(104) = 7.313$, $p < .001$, d =.714 (medium effect size; Cohen, 1988), which contradicts the idea that negative priming effects emerged (Figure 7b).

Figure 7

Accuracy (a) and response time (b) results from the numerical value inhibition task



Note. *** Indicates $p < .001$.

The next analyses were conducted to determine if the negative priming effects elicited from the "domain-specific inhibitory control" task could predict the number of incongruent errors participants made in the "word problems" section, controlling for other cognitive skills that are related to word problem success. First, bivariate correlations were conducted to determine the relations between reading comprehension, numerical competency (arithmetic), working memory, fluid reasoning, domain-general inhibitory control, operational inhibitory control, numerical inhibitory control, and the number of incongruent errors on COIN, IOCN, and IOIN problems (Table 2). As previously mentioned, operational and numerical inhibitory control were measured by subtracting test probe item accuracy from control probe item accuracy.

Table 2

Descriptive statistics and bivariate correlations

	Mean	*SD*	1.	2.	3.	4.	5.	6.	7.	8.	9.
1. Reading Comprehension	93.4	17.3									
2. Arithmetic	122.7	23.5	.436***								
3. Working Memory	15.6	4.46	.172	.234*							
4. Fluid Reasoning	20.2	5.55	.191	.468***	.507***						
5. Domain-gen inhibition	2.05	5.03	-.114	-.247*	-.129	-.126					
6. Operational Inhibition	1.59%	11.3%	-.013	-.037	-.128	-.064	.068				
7. Numerical Inhibition	6.45%	13.7%	-.135	.000	-.217*	-.087	.003	.137			
8. COIN Inc. Errors	1.24	1.04	-.061	.024	-.103	-.121	-.152	.158	.074		
9. IOCN Inc. Errors	1.55	1.79	.062	-.204*	-.267**	-.394***	.185	.192*	.115	.223*	
10. IOIN Inc. Errors	2.48	1.82	-.070	-.125	-.292**	-.309**	.070	.356***	.235*	.440***	.599***

Note. Operational inhibition and Numerical inhibition were presented as percentages to provide more numerical information. * Indicates $p < .05$, ** indicates $p < .01$, and *** indicates $p < .001$.

Bivariate correlations revealed there were some significant correlations between cognitive skills and incongruent errors. Incongruent errors on IOCN problems significantly correlated with arithmetic ($p < .05$), working memory ($p < .05$), fluid reasoning ($p < .001$), and operational inhibitory control ($p = .05$). Incongruent errors on IOIN problems significantly correlated with working memory ($p < .01$), fluid reasoning ($p < .01$), operational inhibitory control ($p < .001$), and numerical inhibitory control ($p < .05$). No cognitive skills significantly correlated with incongruent errors on COIN problems. Finally, the last correlations I wanted to emphasize are that there were no significant correlations between domain-general inhibitory control and both operational inhibitory control ($p = .493$) and numerical inhibitory control ($p = .972$).

Prior to running the regression models, I conducted a preliminary analysis to check if all regression assumptions were met. While most assumptions were met, normality of the incongruent errors on IOCN problems was not satisfied. To address this, a square root transformation with a constant of one was applied to this dependent variable (Osborne, 2002). After this transformation, all assumptions were met.

The first regression model aimed to examine if operational inhibitory control could predict the number of incongruent errors participants made on inconsistent operational problems. The dependent variable for this model was incongruent errors on IOCN problems as this is the only problem type that contained the operational inconsistency and no other inconsistencies. Two models were conducted in this regression. The first model had the cognitive skills (reading comprehension, arithmetic, working memory, fluid reasoning, and domain-general inhibitory control) as the independent variables. The second model had the cognitive skills and operational inhibitory control as independent variables. The first regression model suggests that the cognitive skills could significantly predict incongruent errors on IOCN problems, $F(5,99) = 5.226$, $p < .001$, with 20.9% of the variance in incongruent errors on IOCN problems being explained by cognitive skills (medium effect size; Cohen, 1988). Post hoc analysis revealed fluid reasoning was the only significant predictor in the model $t(99) = -2.922$, $p < .01$. The second regression model suggests that combined, all independent variables could significantly predict incongruent errors on IOCN problems, $F(6,98) = 4.536$, $p < .001$, with all variables accounting for 21.7% of the variance in incongruent errors on IOCN problems (medium effect size; Cohen, 1988). Post hoc analysis revealed that adding operational inhibitory control added 0.9% variance to the model and was not a significant predictor to incongruent errors on IOCN problems, $t(98) = 1.033$, $p = .30$. Fluid reasoning was the only significant predictor to incongruent errors on IOCN problems, $t(98) = -2.927$, $p < .01$ (See Figure A2 in appendix).

The next hierarchical regression model focused on the numerical association and if numerical inhibitory control could predict the number of incongruent errors participants made on inconsistent numerical problems. Paralleling the previous hierarchical model, the dependent variable was the number of incongruent errors on COIN problems. The first model had the cognitive skills as the independent variables. The second model had the cognitive skills and numerical inhibitory control as independent variables. The first regression model suggests that the cognitive skills did not significantly predict incongruent errors on COIN problems, $F(5,99) =1.174$, $p = .327$, with 5.6% of the variance in incongruent errors on COIN problems being explained by the cognitive skills (small effect size; Cohen, 1988). Post hoc analysis revealed that no independent variables could significantly predict incongruent errors on COIN problems. The second regression model suggests that all the independent variables combined did not significantly predict incongruent errors on COIN problems, $F(6,98) = .966$, $p = .433$. Post hoc analysis revealed that adding numerical inhibitory control added 0.1% variance to the model and was not a significant predictor for incongruent errors on COIN problems, $t(98) =.390$, $p = .698$. (See Figure A3 in the appendix).

The final hierarchical regression model focused on both mathematical associations and if operational inhibitory control and numerical inhibitory control could predict the number of incongruent errors participants made on IOIN problems. The first model had the cognitive skills as the independent variables. The second model had the cognitive skills, operational inhibitory control, and numerical inhibitory control as independent variables. The first regression model suggests that combined, all the cognitive skills could significantly predict incongruent errors on IOIN problems, $F(5,99) = 2.728$, $p < .05$, with 12.1% of the variance in incongruent errors on IOIN problems being explained by the cognitive skills (small effect size; Cohen, 1988). Post hoc analysis revealed that no cognitive skills were significant predictors to incongruent errors on IOIN problems, though fluid reasoning was the strongest predictor, $t(99) = -1.901$, $p = .06$. The second regression model suggests that all seven independent variables combined could significantly predict incongruent errors on IOIN problems, $F(7,97) = 4.497$, $p < .001$, with all variables accounting for 24.5% of the variance (medium effect size; Cohen 1988). Post hoc analysis revealed that numerical inhibitory control and operational inhibitory control added 12.4% variance to the model, which caused a significant change to R^2, $\Delta F(2,97) = 7.961$, $p < .001$. Operational inhibitory control was a significant predictor for incongruent errors on IOIN problems, $t(97) = 3.419$, $p < .001$. Numerical inhibitory control was not a significant predictor, though it was the third strongest predictor, $t(97) = 1.644$, $p = .104$. When domain-specific inhibitory controls were added to the model, fluid reasoning became a significant predictor, $t(97) = -2.309$, $p < .05$ (See Figure A4 in appendix).

There were no models examining incongruent errors on either neutral problems or COCN problems as these problem types were consistent with the mathematical associations. However, it may be valuable to examine if the cognitive skills differentially predict consistent problem accuracy relative to inconsistent problem accuracy. Two post hoc multiple linear regression analyses were conducted. The dependent variables were consistent problem accuracy (mean performance on COCN and neutral problems) and inconsistent problem accuracy (mean performance on COIN, IOCN, and IOIN problems). The independent variables were the cognitive skills. Overall, the combined cognitive skills could significantly predict consistent problem accuracy, $F(5,99) = 4.705$, $p < .001$ (19.2% variance; medium effect size; Cohen, 1988), and inconsistent problem accuracy, $F(5,99) = 6.718$, $p < .001$ (25.2% variance; medium effect size; Cohen, 1988). Post hoc analysis revealed that fluid reasoning was the only significant predictor for consistent problem accuracy, $t(99) = 2.723$, $p < .01$, and inconsistent problem accuracy, $t(99) = 3.173$, $p < .01$ (See Figure A5 in appendix).

Research Aim 3: To establish dialogue with individuals to further understand their mathematical association beliefs, classroom experiences that may have contributed to them, and their overall understanding and approach to solving word problems

The first part of the interview focused on gaining a general understanding of how participants think about word problems and their overall practicality. Participants were asked about why they believed word problems are prevalent in all years of mathematics curricula. 77% of coded responses were categorized as narrative-oriented, for example, helping individuals navigate different real-life scenarios. 23% were categorized as paradigmatic, for example, helping individuals develop arithmetic skills. Similarly, when asked if there are real-life applications for word problems, 78% of coded responses were categorized as narrative-oriented, while 22% were categorized as paradigmatic. Next, participants were asked about what skills are important for solving word problems and the general strategies they implement. 53% and 77% of coded responses were categorized as narrative-oriented, such as needing strong reading comprehension skills, or identifying the relations between characters, while 47% and 23% were coded as paradigmatic, such as needing appropriate arithmetic skills and using the keyword method, respectively (Table 3).

Table 3

General understanding of word problems and overall practicality responses

	Narrative-Oriented (total)	Paradigmatic-Oriented (total)
Prevalence of word problems	77% (75)	23% (23)
Real-life applications	78% (57)	22% (16)
Skills required	53% (69)	47% (62)
Word problem strategies	77% (75)	23% (23)

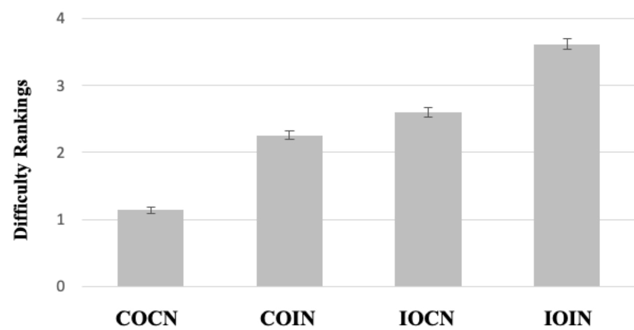
Note. Interview responses to these questions were coded as narrative-oriented, paradigmatic-oriented, both, or neither. Therefore, the total number of responses is provided in parentheses next to the percentages.

The second part of the interview focused on the participants' thoughts regarding the "word problems" section. Prior to explaining the different types of problems, participants were asked to give their initial thoughts or mention if they thought some problems were more challenging. Similar to the first part, I used the paradigmatic- and narrative-oriented themes. Overall, 45% of participants gave responses that were narrative-oriented, such as some problems contained extra information, or it was difficult to figure out the relations between characters. 40% of participants gave responses that were paradigmatic-oriented, such as for some problems the numerical values were hard to manipulate, or the subtraction problems were more difficult. The remaining 15% of participants did not give any remarks.

Once introduced to the problem types, 94% of participants indicated that they noticed for some problems, they could not use all the numerical values to produce the answer. 84% of participants indicated that they noticed the relational terminology could be used to represent both operations. When asked to rank the four problem types from easiest (1) to hardest (4), COCN problems were ranked the easiest (1.14), followed by COIN (2.26), IOCN (2.60), and IOIN problems (3.62) (Figure 8). Further, 58% of participants stated that the operational component gave them more difficulty than the numerical component. 30% of participants stated that the numerical component gave them more difficulty than the operational component. 12% of participants stated both components were of similar difficulty.

Figure 8

Self-reported ranking of problem types from easiest (1) to hardest (4)



Note. COCN: consistent operational and consistent numerical association; COIN: consistent operational and inconsistent numerical association; IOCN: inconsistent operational and consistent numerical association; IOIN: inconsistent operational association and inconsistent numerical association.

The final section of the interview focused on the participants' beliefs and experiences regarding mathematical associations. To my knowledge, this is the first study to directly ask individuals about the associations they may hold and the experiences that may have contributed to them. First, I focused on the operational association and then the numerical association.

Overall, 88% of participants stated they believe in the "more for addition" association. Of the participants that did believe in this association, 23% indicated that their beliefs directly stem from classroom experiences, such as remembering their teacher telling them, or using a keyword poster. The remaining 77% did not give an explicit reason related to the classroom for why they believe in the association, such as stating "more is adding so it is the same as addition." 91% of participants stated they believe in the "less for subtraction" association. Of the participants that did believe in this association, 21% indicated that their beliefs directly stem from classroom experiences, such as remembering their teacher telling them, or using a keyword poster. The remaining 79% did not give an explicit reason related to the classroom for why they believe in the association. Further, 50% of participants indicated that when they experienced an inconsistent operation problem, it was difficult to suppress the "more for addition, less for subtraction" association. Regarding classroom experiences, 59% of participants reported that they remembered seeing a keyword poster in a classroom. Further, 63% of participants remembered a teacher giving suggestions on how to decipher the operation in relational terminology problems. Of the participants that did remember their teachers' suggestions, 39% of them resembled the keyword method (Table 4).

Table 4

Operational association beliefs and experiences

	Yes	No
Believe in "more for addition"	88%	12%
Believe in "less for subtraction"	91%	9%
Hard to suppress operational association	50%	50%
Keyword poster experience	59%	41%
Remember teacher(s) giving operational suggestions	63%	37%

Overall, 80% of participants stated they believe in the numerical association. Of the participants that did believe in this association, 18% indicated that their beliefs directly stem from classroom experiences. The remaining 82% did not give an explicit reason for why they believe in this association, such as, "why would they (the word problem) be trying to trick us," or "if there is a number why would I not use it." 45% of participants indicated that when they experienced an inconsistent numerical problem, it was difficult to suppress the "all numerical values must be used" association. Regarding classroom experiences, 47% of participants indicated they remembered a teacher giving suggestions or lessons on how to determine which numerical values need to be used to solve the problem. However, it was not clear whether the lessons were appropriately emphasizing that all numerical values should be used or not. Further, 87% of participants indicated that they remembered experiencing problems that contained irrelevant numerical information (Table 5).

Table 5

Numerical association beliefs and experiences

	Yes	No
Believe in numerical association	80%	20%
Hard to suppress numerical association	45%	55%
Remember teacher(s) giving numerical suggestions	47%	53%
Prior experience with inconsistent numerical problems	87%	13%

Think-out-Loud Protocol

Unfortunately, I was not able to gather a significant amount of codable data from the think-out-loud section. While all participants that partook in this section were verbal, a majority did not adequately explain the word problem solving process. The most common expressions were participants reading the problem and then either going straight to the calculation step or just providing their answer, without explaining their process. A majority of participants also did not use paper, though they were not required too. Therefore, it was unclear whether participants were taking paradigmatic- or narrative-oriented approaches to their problem solving. A think-out-loud protocol can give valuable insight. Therefore, suggestions and future recommendations are mentioned in chapter 5.

Cluster Analysis Data

Post hoc analyses comparing two independent population proportions were conducted to determine if different themes were elicited from the clusters in *research aim 1*. This analysis calculates the z-score to determine if there are significant differences between two independent proportions. In these analyses, groups B and C were combined as they followed similar trends between consistent and inconsistent problem accuracy and group C only consisted of five participants. This section follows a similar pattern as the overall qualitative analysis.

For the first part of the interview, responses between group A and group B/C elicited no significant differences. There was no significant difference between group A (75%) and group B/C (79%) in the proportion of narrative-oriented responses when participants expressed why they thought word problems were prevalent in all mathematics curricula, $z = 0.759$, $p = .447$. There was no significant difference between group A (75%) and group B/C (83%) in the proportion of narrative-oriented responses when discussing the real-life applications of word problems, $z = 0.850$, $p = .395$. There was no significant difference between group A (55%) and group B/C (48%) in the proportion of narrative-oriented responses regarding which skills are important for word problem solving, $z = 0.806$, $p = .418$. Further, there was no significant difference between group A (72%) and group B/C (85%) in the proportion of narrative-oriented responses regarding strategies participants implement for problem solving, $z = 1.492$, $p = .136$ (Table 6).

Table 6

General understanding of word problems and overall practicality by group

Category	Group A Narrative-Oriented	Group B/C Narrative-Oriented
Prevalence of word problems	75%	79%
Real-life applications	75%	83%
Skills required	55%	48%
Word problem strategies	72%	85%

Group A gave a significantly higher percentage of narrative-oriented responses (51%) when giving their initial reaction to the "word problems" section compared to group B/C (29%), $z = 2.169$, $p < .05$. Further, there was no significant difference between group A (94%) and group B/C (94%) in the percentage of participants that recognized that there were inconsistent numerical problems, $z = 0.14$, $p = .881$. Similarly, there was no significant difference between group A (87%) and group B/C (82%) in the percentage of participants that noticed the relational terminology could be used to represent both operations, $z = 0.635$, $p = .525$. Both groups gave a similar order to ranking the four problem types (Group A: COCN = 1.12, COIN = 2.28, IOCN = 2.51, and IOIN = 3.57; Group B/C: COCN = 1.17, COIN = 2.17, IOCN = 2.73, and IOIN = 3.66) and indicated that the operational component was harder (55% for group A and 64% for group B/C).

The final sections focused on operational and numerical associations. Similar trends were elicited between both groups. There was no significant difference between group A (87%) and group B/C (89%) in the percentage of participants that believed in the "more for addition" association, $z = 0.435$, $p = .664$. Similarly, there was no significant difference between group A (90%) and group B/C (95%) in the percentage of participants that believed in the "less for subtraction" association, $z = 0.912$, $p = .362$. There was no significant difference between group A (48%) and group B/C (55%) in the percentage of participants that reported when they experienced an inconsistent operational problem, it was difficult to suppress the "more for addition, less for subtraction" association, $z = 0.739$, $p = .459$. Regarding classroom experiences, there was no significant difference between group A (55%) and group B/C (66%) in the percentage of participants that remembered seeing a keyword poster in a classroom, $z = 1.058$, $p = .290$. Further, there was no significant difference between group A (63%) and group B/C (63%) in the percentage of participants that remembered a teacher giving suggestions on how to decipher the operation in relational terminology problems, $z = .048$, $p = .962$ (Table 7).

Table 7

Operational association beliefs and experiences by group

	Group A Yes	Group B/C Yes
Believe in "more for addition"	87%	89%
Believe in "less for subtraction"	90%	95%
Hard to suppress operational association	48%	55%
Keyword poster experience	55%	66%
Remember teacher(s) giving operational suggestions	63%	63%

There was no significant difference between group A (82%) and group B/C (76%) in the percentage of participants that believed in the numerical association, $z = 0.711$, $p = .477$. Similarly, there was no significant difference between group A (45%) and group B/C (47%) in the percentage of participants that reported when they experienced an inconsistent numerical problem, it was difficult to suppress the "all numerical values must be used" association, $z =$

0.256, $p = .797$. Regarding classroom experiences, there was no significant difference between group A (52%) and group B/C (36%) in the percentage of participants that remembered a teacher giving suggestions or lessons on how to determine which numerical values need to be used to solve the problem, $z = 1.520$, $p = .129$. Finally, there was no significant difference between group A (84%) and group B/C (92%) in the percentage of participants that remembered experiencing problems that contained irrelevant information, $z = 1.235$, $p = .218$ (Table 8).

Table 8

Numerical association beliefs and experiences by group

	Group A Yes	Group B/C Yes
Believe in numerical association	82%	76%
Hard to suppress numerical association	45%	47%
Remember teacher(s) giving numerical suggestion	52%	36%
Prior experience with inconsistent numerical problems	84%	92%

Chapter 5: Discussion

Domain-specific inhibitory control has been suggested to play a significant role in word problem performance (Lubin et al., 2016; Verschaffel et al., 2020). However, as Van Dooren and Inglis (2015) emphasized, limited work has directly examined this relationship. The goal of the present dissertation study was to examine the role of domain-specific inhibitory control in word problem performance through multiple explicit paradigms and novel approaches. This chapter first discusses the results from each research aim, followed by a general discussion, limitations, future directions, and conclusion.

Research Aim 1: To examine performance on problems that were consistent with mathematical associations compared to inconsistent problems and investigate why participants produced incorrect responses

The findings from the "word problems" section revealed that participants performed significantly worse on problems that contained inconsistencies compared to consistent problems. Further, participants performed significantly worse on problems that contained both numerical and operational inconsistencies compared to problems that contained only one type of inconsistency. The response time data indicated that participants were significantly quicker on neutral and COCN problems compared to problems that contained inconsistencies. Further, participants were significantly quicker on IOCN problems compared to problems that contained numerical inconsistencies (COIN and IOIN). It is not surprising that participants were quicker on operational inconsistent problems compared to numerical inconsistent problems as the keyword method promotes the identification of specific words, rather than understanding the situational narrative (Jaffe et al., 2023). Therefore, it would not take a significant amount of time to identify the operation. With inconsistent numerical problems, if participants were using their numerical association and trying to use all numerical values to produce their answer, extra time would be needed to manipulate all numbers. If they were not using their numerical association, extra time would still be needed to determine which numerical values must be used. These results replicate previous work (e.g., Jiménez & Verschaffel, 2013; Pape, 2003) showing that participants perform worse on inconsistent problems. However, few studies have looked at performance in a college-aged sample. The results suggest that the challenges of inconsistent problems may progress to adulthood.

The examination of errors revealed that error type did differ by problem type. When problems did not contain inconsistencies (neutral and COCN), participants were more likely to make miscalculation errors. Participants were much more likely to make incongruent errors on problems that contained inconsistencies. This suggests that a predominant reason participants were getting inconsistent problems wrong were because they were using, or failing to inhibit, their mathematical associations.

Overall, the word problem data support the idea that participants may be using their associations to facilitate their problem-solving process. Likewise, the accuracy data coincide with the idea that participants may be using the association approach from the inhibitory control model proposed in chapter 1; participants performed significantly worse on inconsistent problems. While there was not a significant difference on the error types for COIN problems, participants made significantly more incongruent errors compared to miscalculation errors on IOCN and IOIN problems, which also supports the model. The inhibitory control model proposed two approaches to solving word problems. Therefore, a cluster analysis was conducted to see if there were subgroups within the sample that coincided with both approaches. Three groups emerged from the cluster analysis. Interestingly, none of the groups directly fit the successful approach. Group A *(n* = 67) showed the strongest performance on all problem types. However, they still followed the trend of performing worse on inconsistent problems, albeit not as severe as the overall sample. Group B (*n* = 33) also showed strong performance on consistent problems (neutral and COCN). However, they performed significantly worse on inconsistent problems – worse than the overall sample. Group C consisted of only five individuals. While it is difficult to generalize the results from this group, it is important to note they exhibited the worst performance of all groups and had the biggest accuracy differences between consistent and inconsistent problems.

The cluster analysis data suggest that participants may be using both the successful and association approach for solving problems. However, the subgroups may differ in how consistently they were able to use the successful approach and inhibit their associations. As illustrated in the semi-structured interview, a vast majority of participants believed in the operational and numerical associations. Supporting this idea, all groups performed worse on inconsistent problems compared to consistent problems. However, compared to accuracy on consistent problems, group A showed stronger performance on inconsistent problems than groups B and C.

Research Aim 2: To investigate how domain-specific inhibitory control relates to word problem performance and the production of incongruent errors

The data from *research aim 1* supports the idea that individuals held mathematical associations and inaccuracies may stem from an inability to inhibit them. However, without direct paradigms used in the "word problems" section, it is difficult to conclude a direct relationship between domain-specific inhibitory control and word problem performance. To address this gap, the current dissertation study also designed domain-specific inhibitory control tasks to directly examine the relationship. To my knowledge, there have been three negative priming studies testing the operational association (e.g., Lubin et al., 2013, 2016; Shum & Chan, 2020). This is the first study to examine the numerical association.

Overall, both the operational and numerical data suggest that negative priming effects emerged. As previously mentioned, priming effects suggest that individuals believe in the association that is being tested for in that paradigm and must inhibit it to produce the correct answer (Lubin et al., 2013; Tipper, 1985). For operational inhibitory control, while the accuracy results were trending towards priming effects, there were significant differences in the response times, similar to Lubin et al. (2013, 2016). Coinciding with participants' self-reported beliefs, this indicates they believe in the operational association. Negative priming effects were elicited in the numerical accuracy data, suggesting that participants believe in the numerical association. However, the response time results suggest the opposite. It is possible that solving consistent prime test items influenced their approach to solving probe test items. As a result, participants may be more likely to use their numerical association rather than first comprehending the situational narrative, which would reduce the time needed to respond. However, it is also possible that the test problems were quicker to read. While this novel paradigm was piloted, it was created explicitly for the study. Therefore, modifications to the experiment, such as independently piloting the probe items to make sure they are of similar length and difficulty, may be needed. I encourage future research to further examine this phenomena.

The accuracy data from the "domain-specific inhibitory control" tasks, along with the "cognitive tests" data, were then used to determine if they could predict incongruent errors made in the "word problems" section. Previous research has suggested that the reason individuals produce incongruent errors may be due to deficits in multiple cognitive skills (Daroczy et al., 2015; Jaffe & Bolger, 2023). Further, relational terminology work has suggested that the reason solvers use their operational association and produce incongruent errors may not solely be due to inhibitory control; reading comprehension may play a significant role (Boonen et al., 2013, 2016). To my knowledge, this is the first study that has used domain-specific inhibitory control data, along with other cognitive skills, to examine word problem success and/or incongruent errors. Overall, some of the evidence suggested that domain-specific inhibitory control may be a strong predictor for incongruent errors, when controlling for other cognitive skills. When predicting IOIN incongruent errors, operational inhibitory control was a significant predictor and the strongest predictor, while numerical inhibitory control trended towards being significant and was the third strongest predictor. Further, these two domain-specific inhibitory control predictors accounted for more variance in the IOIN incongruent error model than all the cognitive skills combined. For incongruent errors on IOCN problems, operational inhibitory control was not a significant predictor. However, an analysis of the data revealed that when applying a squared root transformation to the dependent variable, the predictiveness of each independent variable stayed consistent, except for operational inhibitory control (from $p = .09$ to $p = .30$). The outlier data points in the non-transformed regression revealed that individuals who elicited the strongest negative priming effects, made the most incongruent errors. Interestingly, no cognitive skills, including numerical inhibitory control, could significantly predict COIN incongruent errors. There is not a theoretical reason for numerical inhibitory control to not be a significant predictor in either the COIN or IOIN models. It is possible that other cognitive skills can influence inconsistent numerical problem solving, which would require updates to the proposed model. However, negative priming effects did emerge suggesting that domain-specific inhibitory control plays a role. Overall, this is the first study, to my knowledge, that has measured numerical inhibitory control. Therefore, these results also warrant future research to investigate paradigms that can measure numerical inhibitory control.

While there were multiple cognitive skills that correlated significantly with incongruent errors on different word problem types, fluid reasoning was the only cognitive skill to be a significant predictor in any of the models. Fluid reasoning has correlated with the ability to analyze novel situations (Schneider & McGrew, 2012). Within the context of word problems, it plays an important role in identifying the relations between characters and understanding the underlying narrative (Green et al., 2017). As inhibitory control has shown to be a predictor of fluid reasoning (e.g., Wang et al., 2022), and fluid reasoning has correlated with word problem performance on inconsistent operational problems (e.g., Passolunghi et al., 2022), it is not surprising that it predicted incongruent errors on problems that contained operational inconsistencies.

Arithmetic and reading comprehension were not significant predictors in any of the hierarchical regressions. However, both skills are necessary for successful word problem performance (Jõgi & Kikas, 2015; Pongsakdi et al., 2019; Vilenius-Tuohimaa et al., 2008). Empirical evidence has suggested that younger students may rely on their mathematical associations as they do not have the appropriate reading comprehension skills to understand the narrative (Boonen et al., 2013). Verschaffel et al. (2010) argue that as individuals develop appropriate cognitive skills for problem solving, they may still use their mathematical associations as they have previously produced correct answers. These results suggest one reason participants produced incongruent errors was because of the strategies they implemented. Rather than not comprehending the problem or performing incorrect calculations, participants failed to inhibit their mathematical associations and adapt to novel situations. This suggests that domain-specific inhibitory control may be a better predictor of why individuals make incongruent errors.

Further, empirical work has suggested that different cognitive skills may have varying relationships with consistent and inconsistent problem performance. For instance, solving consistent word problems tend to be a straightforward process (Hegarty et al., 1995). Inconsistent word problem solving may require a more comprehensive understanding of the relationship between characters and objects, which can result in additional demands on cognitive functions (Passolunghi et al., 2022; Verschaffel et al., 2002). However, examining how cognitive skills related to consistent and inconsistent word problem accuracy revealed similar patterns in the predictiveness of each skill. This further suggests that difficulty solving inconsistent word problems compared to consistent problems may not be due to deficits in domain-general cognitive skills.

Finally, an important component of the bivariate correlations comes from the relations between domain-general and domain-specific inhibitory control. Previous work has used domain-general inhibitory control tasks to understand the relations between domain-specific inhibitory control and word problem performance (e.g., Agostino et al., 2010; Passolunghi et al., 2022). However, there were no significant correlations between domain-general and domain-specific inhibitory controls. Further, domain-general inhibitory control did not significantly correlate with and was not a predictor of incongruent errors on any of the inconsistent problem types. Paralleling work in other mathematical domains (e.g., Wilkinson et al., 2019), to understand the relations between domain-specific inhibitory control and word problem solving, domain-specific inhibitory control measures, rather than domain-general measures, like the color Stroop task, should be used.

Research Aim 3: To establish dialogue with individuals to further understand their mathematical association beliefs, classroom experiences that may have contributed to them, and their overall understanding and approach to solving word problems

Word problem research has predominantly taken a quantitative approach. The few studies that have taken qualitative approaches have either observed classroom lessons (e.g, Chapman, 2006), observed the interactions between teachers and students (e.g., Rosales et al., 2012), or have interviewed teachers (e.g., Moleko, 2021; Pearce et al., 2013). No empirical work to my knowledge has interviewed students regarding their mathematical associations. Jiménez and Verschaffel (2013) emphasized that structured interviews with students could give valuable insight to understanding how they navigate word problems. Likewise, with this knowledge, researchers and practitioners could gain a better idea of the relations between domain-specific inhibitory control and word problem success (Van Dooren & Inglis, 2015). The proposed model originates from the idea that prior experiences can influence our problem-solving abilities. Therefore, I aimed to gain a general understanding of how participants think about word problems and their beliefs regarding mathematical associations.

The first part of the interview focused on the participants' general understanding of word problems and their overall practicality. Previous work has stressed the importance of practitioners emphasizing both narrative- and paradigmatic-oriented approaches in their lessons (Chapman, 2006; Depaepe et al., 2010). Both are essential to successful word problem performance. However, when there is more of an emphasis on paradigmatic-oriented approaches (which has been seen in word problem research; Depaepe et al., 2010), it can restrict students from understanding the real-life applications of word problems and the importance of understanding the situational narrative (Depaepe et al., 2014; Verschaffel et al., 2020). Overall, the participants elicited a majority of responses that were characterized as narrative-oriented, suggesting that they understood the practical application and importance of the narrative. This was also shown when talking about what skills are important for solving word problems and the strategies they use.

Focusing on the "word problems" section, their initial thoughts also followed a similar trend with a balanced amount of paradigmatic- and narrative-oriented responses. The ranking of the word problem types were consistent with their overall accuracy. The easiest section was COCN, with the hardest section being IOIN. A majority of participants thought the operational component was harder than the numerical component, which correlated with participants making more incongruent errors on IOCN problems than on COIN problems.

The final section of the interview focused on their mathematical associations and experiences that may have contributed to them. Supporting the quantitative data, a vast majority of participants believed in the operational association. Around half of the participants stated they had trouble suppressing this association when solving inconsistent operation problems. Further, a majority of the participants reported about experiences that may have contributed to this association. These experiences ranged from seeing a keyword poster in the classroom to their teachers promoting the keyword method. While participants were not explicitly asked if their operational association belief was a result of classroom experiences, around a quarter of the participants stated their classroom experiences influenced their beliefs.

Similar trends were seen with the numerical association. A majority of the participants reported that they believe in the numerical association. Further, around half of the participants stated they had trouble suppressing it when solving inconsistent numerical problems. Compared to the operational data, it was not as clear whether participants had experiences that may have contributed to these beliefs. However, despite not being directly asked, around 20% of the participants stated their classroom experiences influenced their numerical association beliefs. Overall, previous work has suggested that solvers' mathematical association beliefs may be influenced by classroom experiences (Lubin et al., 2013; Powell et al. 2022; Verschaffel et al., 2020). In this study, I provided novel evidence that participants self-reported experiences were consistent with their association beliefs.

Regarding the cluster analysis data, similar themes were elicited between group A and group B/C. Since both groups did worse on inconsistent problems compared to consistent problems, it is not surprising that they elicited similar response patterns. The only significant difference was on their initial thoughts of the "word problems" section. Group A gave more narrative-oriented responses while group B/C was more likely to focus on the mathematical structure and elicit paradigmatic-oriented responses. This suggests that individuals in group B/C may have focused more on the mathematical structure during their problem-solving process than group A. This correlated with individuals in group B/C performing worse on inconsistent problems compared to group A.

It was hypothesized that individuals in group B/C would elicit a more paradigmatic-oriented approach when talking about word problems. However, participants in this group understood the importance of the situational narrative, similar to those in group A. While future research is needed, these results suggest that failure to correctly answer inconsistent word problems is not due to a lack of understanding of how they should navigate problems, but rather how they *actually* navigate them and their usage of mathematical associations.

Overall Discussion

Word problems are an essential tool to help students learn how numerical values interact with the real world (Verschaffel et al., 2020). Because of the practical application, solvers must comprehend the narrative and understand the relations between characters and objects to identify which numerical values and operation(s) must be used. Previous work has suggested that students may hold mathematical associations that dissuade them from truly understanding the narrative (Hegarty et al., 1992, 1995; Jiménez & Verschaffel, 2013). This current dissertation expanded upon previous work and gave novel insights into participants' mathematical association beliefs and problem-solving abilities.

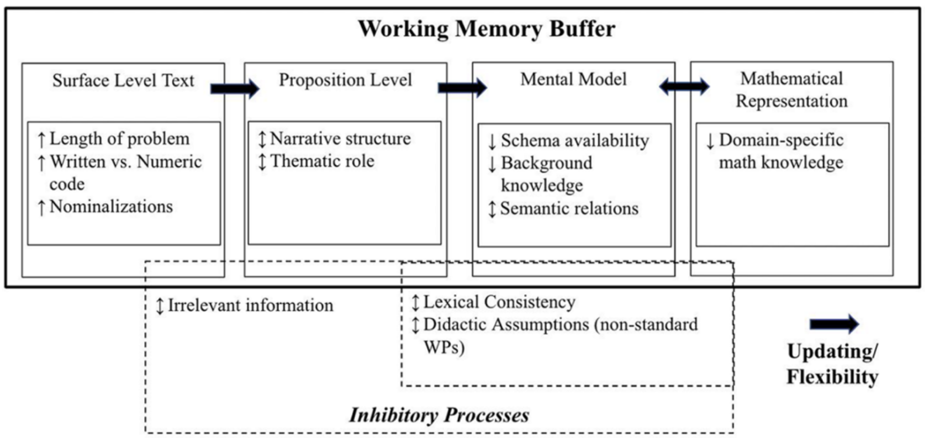
Overall, the results from this study support the proposed model. Participants performed worse on problems that contained inconsistencies compared to consistent problems. A majority of incorrect responses were categorized as incongruent errors on inconsistent problems. Data from the "domain-specific inhibitory control" tasks suggest that individuals held both mathematical associations and that they must inhibit them in order to produce the correct answer. Likewise, the regression models provided novel evidence that domain-specific inhibitory control (or lack thereof) may be a strong predictor as to why solvers made incongruent errors, though future research is required to validate this claim. Finally, supporting the quantitative data, the semi-structured interview revealed that participants do believe in these associations and remembered classroom experiences that may have contributed to them.

The implications of the results highlight the importance of understanding the relationship between domain-specific inhibitory control and word problem performance and the beliefs that solvers hold. From a theoretical perspective, previous word problem models have shown how solvers should navigate problems (e.g., Kintsch & Greeno, 1985). However, as this study has elucidated, word problem solving is a human activity. The mathematical associations that solvers hold influence how they navigate problems. Revisiting the proposed inhibitory control model, the data support the idea that solvers take different paths to producing their answer. Depending on the situational narrative, failure to inhibit one's mathematical associations can lead to an incorrect response.

This model provides a foundation for understanding how domain-specific inhibitory control impacts word problem solving. Further, it sets a precedent for inhibitory control information to be embedded in future models. For example, as research continues, the proposed inhibitory control model (or future frameworks) may update and integrate inhibitory control with other cognitive processes and linguistic word problem features. Individual differences in cognitive abilities can influence how solvers understand and approach the situational narrative (Jaffe & Bolger, 2023). Likewise, the linguistic features of a word problem can pose numerous challenges on cognitive demands (Kintsch & Greeno, 1985; Sweller, 1994, 2011). For instance, Kintch and Greeno's (1985) model highlights the importance of working memory, while the proposed model focuses on the role of inhibitory control. As solvers encounter problems with other linguistic features, such as unfamiliar situational narratives, numerical values presented in word number form, along with problems that contain inconsistent relational terminology and irrelevant numerical values, different strategies and skills may be required for successful solving. Figure 9, which I have also published in *Educational Psychology Review* (Jaffe & Bolger, 2023), demonstrates how different linguistic features can impact cognitive load. While the proposed inhibitory control model provides a novel perspective that elucidates the role of inhibitory control on word problem performance, problems are not limited to operational and numerical inconsistencies. Word problems can contain other linguistic features that can influence performance and require other cognitive skills.

Figure 9

Model of cognitive processes, linguistic factors, and word problems



From an educational perspective, the lack of explicit evidence has halted the integration of inhibitory control information into classrooms (Van Dooren & Inglis, 2015). In fact, teacher-based research has suggested that many practitioners may not be aware of the role that inhibitory control plays in word problem success (Moleko, 2021; Pearce et al., 2013). For instance, Pearce et al. (2013) interviewed 70 2nd to 5th grade mathematics teachers where a majority reported that students' struggles originate from their comprehension skills and lack of vocabulary knowledge. When asked about the strategies they implement in the classroom, the most common response was the keyword method; a strategy that can further solidify students' mathematical associations. Further, recent intervention techniques have predominantly focused on either embedding language comprehension instruction into word problem lessons (e.g., Fuchs et al., 2021) or using schema-based approaches to help students reduce working memory demands (e.g., Fuchs et al., 2019). Developing reading comprehension skills and strategies to reduce working memory demands are essential for word problem success (Jaffe & Bolger, 2023). However, based on the medium to strong effect sizes elicited in this study, there is also a practical application for the proposed inhibitory control model. Therefore, for problems that contain inconsistencies, it may also be important that techniques are in place to help students inhibit their mathematical associations.

Chapter 1 offered revisions to Kintch and Greeno's (1985) word problem model. Similarly, based on the results and effect sizes from the current dissertation study, I offer an example of how this information may be integrated into classroom lessons. Schema-based approaches, arguably one of the most common interventions in word problem research and whose foundations originate from Kintch and Greeno's model, promote a scaffolding technique to help students conceptualize the situational narrative. Lessons encourage solvers to break down the problem into set schemas, underline relevant information, and draw diagrams to understand the relations between characters and objects. As solvers develop their schemas and read the problem for the first time, they draft an equation with unknown variables (letters) to represent the problem. As they re-read the problem, they check that they constructed accurate schemas and replace the letters with the appropriate numbers (See Fuchs et al., 2021; Powell, 2011 for more information on schema-based approaches).

Schema-based approaches give solvers a path to correctly solve inconsistent problems. However, the mathematical associations that individuals hold may supersede the production of certain schemas (Jaffe & Bolger, 2023; Verschaffel et al., 2020). To help solvers inhibit their associations, schema-based approaches may incorporate additional steps. With relational terminology problems, lessons can encourage students to visually illustrate which character contains more or less of an object than the other, independent of solving the overall problem. Then, when they have constructed their equivalent numerical equation, they can compare the operation to their illustration to determine if the relations are correct. With regards to the numerical component, it is essential that solvers construct representations for each numerical value rather than assume they will all be used. For instance, a solver can illustrate each character, the objects they hold, and use arrows to indicate which characters had a relation or transaction with each other. When solving the problem, they can physically cross off characters (and numbers) that do not relate to the word problem question. For instance, in the problem "John has 4 apples. He gave 3 apples to Mary. Zach has 1 orange. How many apples does John have now?" A solver could eliminate their illustration of Zach and his 1 orange as he did not have a relation with John, nor did he possess the same object(s) as John. While this is only one example of how to help individuals inhibit their associations, it is important that students develop techniques that can be applied to both consistent and inconsistent problems.

Overall, this study revealed explicit evidence that individuals believe in mathematical associations and need to inhibit them for successful problem solving. As a result, there may now be a clearer path for inhibitory control information to expand into classrooms, whether through lessons, or the types of problems students encounter. Future directions are discussed in the next section.

Limitations and Future Research

The current dissertation study did come with limitations. First, while a think-out-loud section could have given valuable insight to understanding how solvers navigate word problems and how mathematical associations can influence their strategies, this study was unfortunately not able to collect codable data from this section. Modifications to either the difficulty of the problems, which may encourage participants to talk and explain their process more, and/or instructions will be needed for future research.

Next, while this study helped identify a more direct relationship between domain-specific inhibitory control and word problem performance, the relations between domain-specific inhibitory control and classroom experiences were only correlational. Mathematical problem solving is a social process (Woods et al., 1995), and while the data suggest that beliefs are influenced by classroom experiences, I am not able to make a definitive conclusion from these results. Future research should investigate which factors or experiences predominately contribute to solvers' beliefs. For instance, Verschaffel et al. (2010) proposed that mathematical associations may develop and strengthen from predominantly experiencing consistent problems, while classroom data have identified the prevalence of teachers using paradigmatic-oriented approaches (e.g., Chapman, 2006; Depaepe et al., 2010). In fact, this study identified that a majority of students remember seeing a keyword poster in a classroom. Future work, whether it is more in-depth interviews, or classroom studies, should focus on identifying these factors. Once this has been examined, research can then focus on designing interventions or studies to dissuade students from using their associations. Jaffe and Bolger's (2023) literature review proposed potential areas for research to investigate, such as examining: (a) the effect of giving students problems a larger percentage of problems that are inconsistent with their mathematical associations, and (b) the impact of teachers explicitly stating that mathematical associations cannot be used for successful problem solving and showing why.

Another limitation from this study derives from the scope of the mathematical associations examined. "More for addition and less for subtraction" and all numerical values must be used are not the only mathematical associations. Within the realm of operational associations, there are other words that have been associated with mathematical operations, such as "altogether" for addition. Further, a person's familiarity of the situational background may need to be inhibited if the situational narrative is semantically incongruent from one's mathematical knowledge (Bassok et al., 1998; Bassok, 2001; Gros et al., 2019). For example, when objects in a word problem belong to the same taxonomic class (e.g., green marbles and red marbles), individuals are likely to believe the operation is addition or subtraction. However, when they do not belong to the same class (e.g., vases and flowers), individuals are more likely to think the operation is multiplication or division (Bassok et al., 2008; Gros et al., 2021). This current study showed that domain-general inhibitory control did not significantly correlate with domain-specific inhibitory control. Therefore, future work is needed to determine what contributes to students believing in other mathematical associations and how they impact word problem performance.

Finally, I encourage future research to investigate the direct relations between domain-specific inhibitory control and word problem performance in younger populations – populations that are still actively solving word problems in their school curricula. The current dissertation study identified that participants held mathematical associations that may have been introduced to them over a decade earlier. As these participants are still failing to inhibit their associations in adulthood, it is essential to understand when students start to develop them. Empirical work has identified that early mathematics performance is a strong predictor of future mathematics performance (Claessens & Engel, 2013). Likewise, Verschaffel et al. (2010) emphasized that the more opportunities students are able to use their associations and be successful, the harder it becomes to inhibit them. Therefore, understanding when students are experiencing lessons or material that can promote associations and how this influences their early word problem understanding are essential next steps in research.

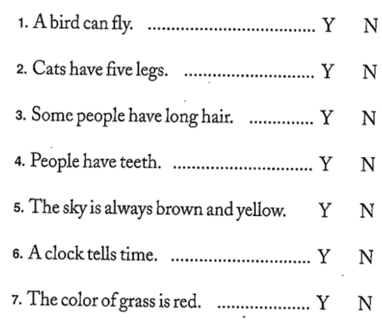
Conclusion

Word problems are a valuable part of mathematics education and help bridge the gap between mathematics and the real-world. Therefore, it is essential that students develop appropriate strategies to comprehend the situational narrative and successfully identify the numerical values and operation(s) needed to produce the correct answer. The current study, through quantitative and qualitative measures, demonstrated that individuals may use their mathematical associations to identify the mathematical components and at times, are unable to inhibit them when solving inconsistent problems. With a clearer understanding of the relationship between domain-specific inhibitory control and word problem performance, there are now more promising paths to integrating this information into educational domains.

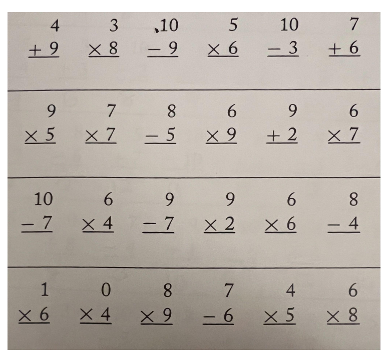
Appendices and Supplemental Materials

Supplemental 1 (S1): Cognitive Skill Tests and Measures

Reading Fluency Task. In this task, participants were given a three-page booklet with 128 one-sentence statements. Participants had to determine whether the statements were true or false. They had three minutes to complete as many as they could. Scores were measured by the total amount of correct responses. An example of the statements is provided below.


1. A bird can fly. .... Y N
2. Cats have five legs. .... Y N
3. Some people have long hair. .... Y N
4. People have teeth. .... Y N
5. The sky is always brown and yellow. Y N
6. A clock tells time. .... Y N
7. The color of grass is red. .... Y N

Math Fact Fluency. In this task, participants were given a two-page booklet containing 160 arithmetic problems. Participants had three minutes to complete as many problems as they could. Problems contained all four operations and all answers were either single- or double-digit. Scores were measured by the total amount of correct responses. Example problems are provided below.



4 + 9	3 × 8	10 − 9	5 × 6	10 − 3	7 + 6
9 × 5	7 × 7	8 − 5	6 × 9	9 + 2	6 × 7
10 − 7	6 × 4	9 − 7	9 × 2	6 × 6	8 − 4
1 × 6	0 × 4	8 × 9	7 − 6	4 × 5	6 × 8

Numbers Reversed. In this task, participants heard a series of numbers. They were instructed to respond back by recalling the numbers in the reverse order. For example, if they heard "1…2", the correct response would be "2…1." This section consisted of 30 trials. Trials started with two numbers and gradually increased to nine numbers. The task is completed when either the participant finishes all 30 trials or incorrectly answers three trials in a row. Scores were measured by the total amount of correct responses.

Numerical Reasoning. In this task, participants were presented with a series of numerical values, with either one or two numbers missing within the pattern. They were instructed to identify the missing number(s). This section consisted of 32 trials. This task is completed when either the participant finishes all 32 trials or incorrectly answers three trials in a row. Scores were measured by the total amount of correct responses. Example problems are provided below.

13	15		19

27		3	1

Color Word Stroop Task. In this task, participants were presented with a series of color words (e.g., red, green, blue) in various colors and were instructed to say the color of the text, not what the word says. This task consisted of two trials. Both trials consisted of 25 words in a five-by-five grid and participants were instructed to say the colors as quickly and accurately as possible. In the first trial, all the colors matched the respective word (e.g., the word "red" was in red text). In the second trial, all the colors did not match the respective word (e.g., the word "red" was in blue text). Times were recorded for how long it took participants to complete each trial. If a participant elicited an incorrect response, a time penalty was added. To calculate total times with penalties, I used Stroop's (1935) formula: total time + ((2*mean time per word)*number of incorrect responses). Scores were measured by subtracting the completion time of trial 1 from trial 2. Pictures of each trial are presented below.

Trial 1 **Trial 2**

Supplemental 2 (S2): Interview Guide

(a) General Understanding and Thoughts about Word Problems: This section aims to evaluate participants' understanding and thoughts regarding word problems. Interview questions include:

- Why do you think word problems are prevalent in all years of education?
- Do you think there is a practical or real-life application for word problems?
- What skills do you think are important for solving word problems?
- Are there any strategies you use to navigate and solve word problems?

(b) Word Problems: Prior to discussing problem types, participants were first asked:

- Do you have any initial thoughts or comments about the word problems you solved?
- Did you find any of the problems to be more challenging than others?

Studies have suggested that participants may be unaware of inconsistent mathematical associations embedded within problems (e.g., Hegarty et al., 1995; Ng et al., 2017). Therefore, having participants give their initial thoughts before mentioning the problem types could allow me to further understand how they process mathematical associations. Following their responses, the researcher explained the problem types the participants encountered and asked the following questions:

- Did you notice that for some problems, you could not use and manipulate all the numerical values to produce the answer?
- Did you notice that for some problems, the relational terminology ("more" and "less") may have been different than the expected operation? For example, "more" being used in a subtraction problem or "less" being used in an addition problem.
- Can you rank the problem types from easiest to hardest? If you think some of the problem types were of the same difficulty, you can give them the same ranking.
- Why did you pick this order?
- Do you have any additional comments or feedback about the problems you encountered?

(c) Mathematical Associations: This section focused on participants' mathematical associations. The interview questions include:

- When you see the word "more" in a word problem, do you assume the mathematical operation is going to be addition? Why or why not?
- Similarly, when you see the word "less", do you assume the mathematical operation is going to be subtraction? Why or why not?
- When you encountered a problem where "more" was used in a subtraction problem, or "less" was used in an addition problem, was it difficult to suppress the idea that "more" means addition and "less" means subtraction?
- When you see a number in a word problem, do you assume the number will be used somehow to help you get the correct answer? Why or why not?

- When you encountered a problem where not all the numbers were used, was it difficult to suppress that idea that all numbers need to be used?
- Do you remember being in a classroom that had a keyword poster to help you figure out the operation of the problem?
- Do you remember having a teacher give suggestions on how to decipher the operation with relational terminology problems.
- Do you remember experiencing problems where not all the numbers were used to produce the correct answer?
- Do you remember having a teacher give suggestions on how to decipher which numbers are going to be used to solve the problem?
- Is there anything else you would like to mention?

Supplemental 3 (S3): Coding Scheme

The coding scheme for the semi-structured interview and think-out-loud protocol was adapted and modified from Chapman (2006) and Depaepe et al. (2010). The schemas in these studies were used in classroom-based settings and involved lessons and class discussions. As this study focused on understanding participants' thoughts and approaches to word problems, some of the subthemes they used were not applicable. Described below are the characteristics and subthemes for paradigmatic-oriented approaches and narrative-oriented approaches. A limited number of questions in the interview were coded with these themes, therefore, I did not break down responses by subthemes.

Paradigmatic-oriented*:* Emphasizing the general mathematical structure of the underlying problem, independent of the situational narrative.

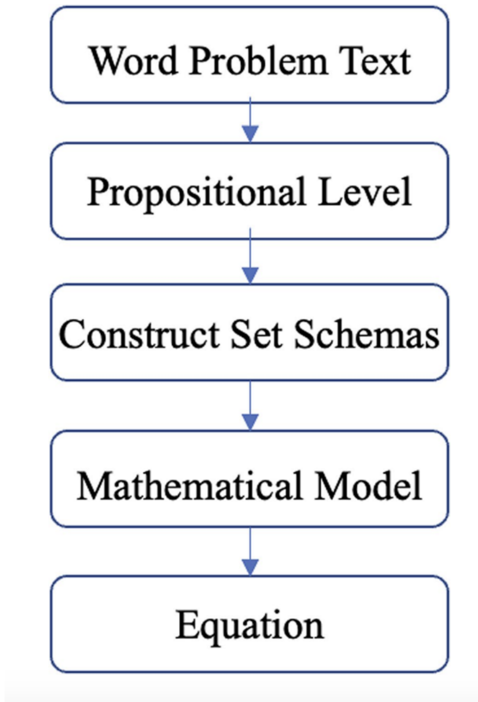
> ***P1*:** Applying a prototypical theme – Focusing on transforming the numerical values to a mathematical arithmetic equation (Depaepe et al., 2010).
> ***P2*:** Addressing the underlying mathematical structures – Emphasizing components of the mathematical structure, (whether in the word problem or equivalent equation), without acknowledging the linguistic context (Depaepe et al., 2010).
> ***P3*:** Mathematical strategies – Strategies used to help produce the resultants that are independent from the situational context. This can include the keyword method as solvers are not using words like "more" or "less" within its situational context.
> ***P4*:** Mathematical skills – Emphasizing problem solving skills that are independent of understanding the situational narrative (e.g., arithmetic skills)

Narrative-Oriented*:* Emphasizing the real-world context in which the problem is embedded in and understanding the situational context.

> ***N1:*** Defining and understanding notions involved in the problem – Focusing on the meaning and relations between characters, objects, specifications, and roles (Depaepe et al., 2010).
> ***N2*:** Real-life experiences and prior knowledge – Relating a word problem to prior experiences or real-life circumstances to help one solve the problem (Depaepe et al., 2010).
> ***N3:*** Mathematical strategies – Emphasizing strategies that either focus on understanding the relations between characters and objects, understanding the problem within the situational context, or applying real-world knowledge to their problem-solving process.
> ***N4:*** Mathematical skills – Skills that are important to problem solving that emphasize understanding the linguistic component of the problem.

Figure A1

Adaptation of Kintsch and Greeno's (1985) Model



Note. Published by Jaffe & Bolger (2023)

Figure A2

Hierarchical regression for IOCN incongruent errors

ANOVA

Model		Sum of Squares	df	Mean Square	F	p
H_0	Regression	5.446	5	1.089	5.226	< .001
	Residual	20.634	99	0.208		
	Total	26.079	104			
H_1	Regression	5.668	6	0.945	4.536	< .001
	Residual	20.411	98	0.208		
	Total	26.079	104			

Note. Null model includes Reading Comp, Arithmetic, Working Memory, Fluid Reasoning, Domain Gen. Inhibition

Coefficients ▼

Model		Unstandardized	Standard Error	Standardized	t	p
H_0	(Intercept)	1.950	0.313		6.233	< .001
	Reading Comp	0.005	0.003	0.173	1.734	0.086
	Arithmetic	−0.001	0.002	−0.057	−0.501	0.617
	Working Memory	−0.011	0.012	−0.099	−0.947	0.346
	Fluid Reasoning	−0.030	0.010	−0.334	−2.922	0.004
	Domain Gen. Inhibition	0.015	0.009	0.152	1.628	0.107
H_1	(Intercept)	1.927	0.314		6.144	< .001
	Reading Comp	0.005	0.003	0.172	1.720	0.089
	Arithmetic	−0.001	0.002	−0.057	−0.497	0.620
	Working Memory	−0.010	0.012	−0.087	−0.827	0.410
	Fluid Reasoning	−0.030	0.010	−0.335	−2.927	0.004
	Domain Gen. Inhibition	0.015	0.009	0.149	1.593	0.114
	Operational Inhibition	0.004	0.004	0.093	1.033	0.304

Note. H_0: $R^2 = .209$; H_1: $R^2 = .217$. $\Delta R^2 = .08$, $\Delta F(1,98) = 1.067$, $p = .30$

Figure A3

Hierarchical regression for COIN incongruent errors

ANOVA

Model		Sum of Squares	df	Mean Square	F	p
H_0	Regression	6.330	5	1.266	1.174	0.327
	Residual	106.718	99	1.078		
	Total	113.048	104			
H_1	Regression	6.495	6	1.082	0.996	0.433
	Residual	106.553	98	1.087		
	Total	113.048	104			

Note. Null model includes Arithmetic, Reading Comp, Working Memory, Fluid Reasoning, Domain Gen. Inhibition

Coefficients

Model		Unstandardized	Standard Error	Standardized	t	p
H_0	(Intercept)	1.996	0.708		2.819	0.006
	Arithmetic	0.005	0.005	0.103	0.836	0.405
	Reading Comp	−0.005	0.007	−0.087	−0.793	0.430
	Working Memory	−0.014	0.027	−0.062	−0.540	0.590
	Fluid Reasoning	−0.027	0.023	−0.142	−1.134	0.259
	Domain Gen. Inhibition	−0.034	0.021	−0.163	−1.608	0.111
H_1	(Intercept)	1.936	0.728		2.661	0.009
	Arithmetic	0.004	0.006	0.098	0.792	0.430
	Reading Comp	−0.005	0.007	−0.081	−0.729	0.468
	Working Memory	−0.012	0.027	−0.053	−0.454	0.651
	Fluid Reasoning	−0.027	0.024	−0.142	−1.128	0.262
	Domain Gen. Inhibition	−0.034	0.021	−0.162	−1.595	0.114
	Numerical Inhibition	0.003	0.008	0.040	0.390	0.698

Note. H_0: $R^2 = .056$; H_1: $R^2 = .057$. $\Delta R^2 = .01$, $\Delta F(1,98) = 0.152$, $p = .698$

Figure A4

Hierarchical regression for IOIN incongruent errors

ANOVA

Model		Sum of Squares	df	Mean Square	F	p
H_0	Regression	41.919	5	8.384	2.728	0.024
	Residual	304.271	99	3.073		
	Total	346.190	104			
H_1	Regression	84.820	7	12.117	4.497	< .001
	Residual	261.370	97	2.695		
	Total	346.190	104			

Note. Null model includes Arithmetic, Reading Comp, Working Memory, Fluid Reasoning, Domain Gen. Inhibition

Coefficients

Model		Unstandardized	Standard Error	Standardized	t	p
H_0	(Intercept)	4.872	1.196		4.075	< .001
	Arithmetic	0.003	0.009	0.034	0.283	0.778
	Reading Comp	-7.482×10^{-4}	0.011	−0.007	−0.068	0.946
	Working Memory	−0.073	0.045	−0.179	−1.624	0.108
	Fluid Reasoning	−0.075	0.040	−0.229	−1.901	0.060
	Domain Gen. Inhibition	0.009	0.035	0.026	0.264	0.793
H_1	(Intercept)	4.206	1.146		3.668	< .001
	Arithmetic	0.001	0.009	0.017	0.154	0.878
	Reading Comp	0.001	0.010	0.011	0.108	0.915
	Working Memory	−0.044	0.043	−0.107	−1.018	0.311
	Fluid Reasoning	−0.076	0.037	−0.230	−2.039	0.044
	Domain Gen. Inhibition	0.004	0.033	0.011	0.126	0.900
	Operational Inhibition	0.050	0.014	0.307	3.419	< .001
	Numerical Inhibition	0.020	0.012	0.151	1.644	0.104

Note. H_0: $R^2 = .121$; H_1: $R^2 = .245$. $\Delta R^2 = .124$, $\Delta F(2,97) = 7.961$, $p < .001$

Figure A5

Regression models and bivariate correlations for cognitive skills predicting (a) consistent problem accuracy and (b) inconsistent problem accuracy

a

ANOVA ▼

Model		Sum of Squares	df	Mean Square	F	p
H_1	Regression	0.138	5	0.028	4.705	< .001
	Residual	0.580	99	0.006		
	Total	0.718	104			

Note. The intercept model is omitted, as no meaningful information can be shown.

Coefficients

Model		Unstandardized	Standard Error	Standardized	t	p
H_0	(Intercept)	0.925	0.008		114.116	< .001
H_1	(Intercept)	0.773	0.052		14.806	< .001
	Reading Comp	-1.770×10^{-4}	4.833×10^{-4}	−0.037	−0.366	0.715
	Arithmetic	6.265×10^{-4}	4.023×10^{-4}	0.177	1.557	0.123
	Working Memory	-3.367×10^{-5}	0.002	−0.002	−0.017	0.986
	Fluid Reasoning	0.005	0.002	0.315	2.723	0.008
	Domain Gen. Inhibition	−0.001	0.002	−0.079	−0.843	0.401

Note. H_1: $R^2 = .192$.

b

ANOVA

Model		Sum of Squares	df	Mean Square	F	p
H_1	Regression	0.526	5	0.105	6.718	< .001
	Residual	1.550	99	0.016		
	Total	2.076	104			

Note. The intercept model is omitted, as no meaningful information can be shown.

Coefficients

Model		Unstandardized	Standard Error	Standardized	t	p
H_0	(Intercept)	0.797	0.014		57.835	< .001
H_1	(Intercept)	0.513	0.085		6.018	< .001
	Reading Comp	-7.745×10^{-4}	7.899×10^{-4}	−0.095	−0.981	0.329
	Arithmetic	8.443×10^{-4}	6.574×10^{-4}	0.141	1.284	0.202
	Working Memory	0.005	0.003	0.145	1.425	0.157
	Fluid Reasoning	0.009	0.003	0.353	3.173	0.002
	Domain Gen. Inhibition	-1.233×10^{-4}	0.003	−0.004	−0.049	0.961

Note. H_1: $R^2 = .252$.

	Mean	*SD*	1.	2.	3.	4.	5.	6.
1. Reading Comprehension	93.4	17.3						
2. Arithmetic	122.7	23.5	.436***					
3. Working Memory	15.6	4.46	.172	.234*				
4. Fluid Reasoning	20.2	5.55	.191	.468***	.507***			
5. Domain-gen inhibition	2.05	5.03	-.114	-.247*	-.129	-.126		
6. Consistent problem Accuracy	0.925	0.083	.109	.328***	.203*	.400***	-.158	
7. Inconsistent problem Accuracy	0.797	0.141	.059	.299**	.341***	.474***	-.091	.749***

IRB Approval Letter

UNIVERSITY OF MARYLAND

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DATE:	March 8, 2023
TO:	Joshua Jaffe, B.S.
FROM:	University of Maryland College Park (UMCP) IRB
PROJECT TITLE:	[2017977-1] Inhibition is Key: A Cognitive Approach to Successful Word Problem Solving
SUBMISSION TYPE:	New Project
ACTION:	DETERMINATION OF EXEMPT STATUS
DECISION DATE:	March 8, 2023
REVIEW CATEGORY:	Exemption category #45CFR46.104(d)(2)(ii)

Thank you for your submission of New Project materials for this project. The University of Maryland College Park (UMCP) IRB has determined this project is EXEMPT FROM IRB REVIEW according to federal regulations.

We will retain a copy of this correspondence within our records.

If you have any questions, please contact the IRB Office at 301-405-4212 or irb@umd.edu. Please include your project title and reference number in all correspondence with this committee.

This letter has been electronically signed in accordance with all applicable regulations, and a copy is retained within University of Maryland College Park (UMCP) IRB's records.

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