ABSTRACT

Title of dissertation: THE CONTRIBUTION OF INHIBITORY CONTROL ON CHILDREN'S GESTURE USE IN AN EARLY MATHEMATICAL ENVIRONMENT

Raychel J. Barkin, Doctoral Candidate, 2023

Dissertation directed by: Professor Geetha B. Ramani
Department of Human Development and Quantitative Methodology

Early academic scores are strong and robust predictors of children's later school and career performance (Duncan et al., 2007; Rose, 2006). However, the USA ranks well below other countries on math scores (27th out of 34; OECD, 2013), and have been marked as particularly inadequate at "mathematics tasks with higher cognitive demand(s)". Thus, it is important to focus on the mechanisms which may contribute to differences in early mathematics problem solving and find tools that are uniquely suited to addressing this issue. One advantageous strategy young children use during math problem solving are hand gestures. Gestures are one of several overtly observable strategies in math contexts(e.g., counting on fingers vs. counting out loud without gestures), but have been specifically recognized as useful given their ability to reduce the user's working memory load during math contexts (Goldin-Meadow & Wagner, 2005). As children get older, the type and frequency of strategies used are

reported to shift from basic to more advanced and efficient (Siegler, 1987). This pattern is often seen as younger children using more overtly observable strategies (e.g., finger counting), whereas older children rely on more implicit strategies (e.g., memory retrieval of math facts, Geary et al., 1991). However, less is known about how differences in children's concurrent domain-general abilities (e.g., working memory, inhibitory control) and domain-specific knowledge (e.g., math specific) contribute to strategic use of gesture during arithmetic problem solving. This line of research is vital given that gestures may be especially advantageous based on their capacity to bolster mental resources needed for problem solving. Using the Gestures in Math Environments model (GME model; Gordon & Ramani, 2021) as a framework, the current study provides a comprehensive assessment of the factors underlying children's domain-general and specific abilities, and provides evidence as to their relation to children's use of gesture as a strategy during arithmetic problem solving. Furthermore, it tests a newly proposed adaptation to the GME model where inhibitory control plays a moderating role on the relation between children's working memory and use of gesture.

One-hundred-thirty-seven 4- to 7-year-old children and their parents participated in this study. All children completed two sessions; an autonomous online-game based assessment and a video recorded zoom session regulated by a trained research assistant. At each session, children completed measures of inhibitory control, early mathematical knowledge, and working memory. Their gesture use was video recorded during one measure where children partake in arithmetic problem solving. Parents completed a standardized measure assessing their child's inhibitory control and working memory abilities. Using structural equation modeling, the relations between all measures and a consideration of how each corresponded to a set of comprehensible latent factors (one factor each for inhibitory control, working memory, and math) were examined.

Further examination of how each factor related to children's use of gesture was investigated.

In line with the original GME model, working memory ability was a unique predictor of children's use of gesture above and beyond impacts of age, math knowledge, inhibitory control, and gender. While there is not any evidence from the current study to support the proposed moderation between inhibitory control and working memory on gesture use, a modification to the GME model with the addition of gender is subsequently recommended.

THE CONTRIBUTION OF INHIBITORY CONTROL ON CHILDREN'S GESTURE USE IN AN EARLY MATHEMATICAL ENVIRONMENT

by

Raychel J. Barkin

Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
2023

Advisory Committee:

Professor Geetha Ramani, Chair
Professor Janet Walkoe, Dean's Representative
Professor Donald Joseph Bolger
Professor Richard Prather
Professor Meredith Rowe

Acknowledgements

I have spent the past 4 and a half years learning how to operationalize human behavior. Yet here I am at the end of it all trying to write this section based on innumerable exploits from people whose significance is immeasurable; and thus, impossible to quantify.

I'll try my best. Thank you…

To all the families who participated in my research and the funders who made this work possible.

To my committee members who turned this study into something I am proud of.

To Geetha, as I could not and *would not* have done graduate school without you. I am endlessly grateful to have you as a mentor. Working with you has been one of the absolute honors of my life.

To the ECI Lab members, with special nods to Emily, Gillian, Neela, and Nicole for your encouraging words and making this whole research thing so fun.

To my grad fam, Brennan, Jac, Kat, for the years of friendship, albums worth of snapchats, and countless pizzas.

To my friends since the beginning, Liz, Jen, and Steph for always reminding me to be myself and that I am not alone.

To my person, Gianna for the daily texts, proofreading, and unparalleled wit which has kept me sane for most of my adult life.

To my in-laws, Hannah, Leslie, Randy, Zach & Cassie. Either you are all interested in what I do or are the best actors of all time. It is rare to find such marvelous people, and I am lucky to have each of you in my life.

To my family, Mary, Mom, Padre. If Apple charged for facetime minutes, we'd all be in trouble. I am indebted to you all and can only hope to pay back some of what you've given me with time.

To Darnise. An hour a week with you probably wasn't enough.

To Artemisia and Sullivan for your constant companionship and occasional hairball (to keep me guessing, I suppose).

And lastly to Jake, my best friend. For every time you made coffee, fixed breakfast, dragged me outside, and poured us a glass of wine. Without you, I could never have pursued this dream. I love you.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

Statement of the Problem

Early academic scores are some of the strongest and most robust predictors of children's later school performance (Duncan et al., 2007; Jordan et al., 2009). Mathematics achievement is one particularly important academic factor as it affects decisive life outcomes such as educational attainment, employment rates, and overall income (Geary, 2011; Ritchie & Bates, 2013). To understand the components of early mathematical education that are most critical to later success, the US Department of Education formed a National Mathematics Advisory Panel who were tasked with reviewing all available research and trends pertaining to children's math education in the United States (2008). Most notably, their summary suggests that early understanding of arithmetic facts, procedures, and conceptual knowledge are lacking for students in the US, leading to later difficulties in higher-level mathematics such as algebra. Given the links between early mathematics and later life outcomes, the US children's inadequacies in arithmetic are cause for national concern.

Early arithmetic competence has been studied at length; children are able to solve addition transformations by approximately age 5 or 6 years old by answering simple questions such as "What is 3 + 2?", or even similar story versions of the same problem type "John has four marbles. Harry gives him two more marbles. How many marbles does John have?" (e.g., Jordan et al., 1992, 1994; Shrager & Siegler, 1998). The ability to solve verbal calculations requires mastery of a series of foundational mathematical skills. Once a child has formed this basis of understanding for one math topic and begins to learn another, these valuable mathematical connections between topics allow for practical behavioral shifts. For example, mastery of central concepts such as inversion and associativity indicate that a child has formed an understanding of the interrelation between functions of addition and subtraction (Prather & Alibali, 2009). For more foundational skills, when a young child has mastered the principles of counting and is learning about addition, they should be able to flexibly and strategically shift between less sophisticated problem-solving approaches based on counting (e.g., finger counting to find the sum) to more efficient strategies for addition specifically (e.g., committing math facts about simple sums to memory and recalling them). Thus, the overtly observable variations within children's approaches to addition problem solving can be further used to specify developmental patterns in early mathematical understanding (Ashcraft, 1982; Carpenter & Moser, 1984; Siegler, 1996; Siegler & Shrager, 1984). According to Siegler and Jenkins (2014) strategies include "any procedure that is nonobligatory and goal directed". The strategies which children employ while solving arithmetic problems may vary across three dimensions; their levels of domain-specific arithmetic knowledge, their domain-general cognitive abilities such as executive function, and the interaction between the two.

Executive function can be defined as the set of mental resources which allow us to hold and work through relevant information in our mind, focus attention on what is important, as well as flexibly think and engage during problem solving. A common theoretical model of executive function presents three separate, yet interacting processes; namely cognitive flexibility, working memory, and inhibitory control (Miyake et al., 2000). Extensive interdisciplinary research has attempted to untangle how each component of executive function may contribute to individual variation in children's mathematical abilities (see Clements et al., 2016 for a review). While more research is necessary to qualify the directionality and strength of each relation, common models of children's mathematics problem solving and learning often attribute success to a combination of mathematical content knowledge (domain-specific), and executive function skills (domain-general) which allow for successful mathematics problem solving and learning (e.g., Huttenlocher et al., 1994; Overlapping-Waves Model, Siegler, 1996; SCADS Model; Shrager & Siegler, 1998). Each of these frameworks provides unique and compelling explanations of the behaviors children may exhibit during such arithmetic problem solving.

However, these models do not provide a foundation for researchers to consider how children's use of hand gestures may be separately beneficial from strategies in other modalities (e.g., speaking out loud or mental math). Prior work has shown that gestures can facilitate children's acquisition of novel math concepts (Broaders et al., 2007), primarily through a reduction of cognitive demands (Cook et al., 2012; Goldin-Meadow et al., 2001) as well as a direction of attention (Wakefield et al., 2018). In other words, gestures provide a pipeline to learning mathematical content through an embodied pathway which benefits overall cognition. This core mechanism is often discussed in relation to how a users' self-produced gestures have the capacity to reduce "cognitive load" (Cognitive Load Theory; Sweller, 1988).

Furthermore, prior research regarding mathematics often does not account for how the use of gesture as a problem-solving strategy may be different than strategies of a verbal or mental modality. Research regarding children's arithmetic strategies is often presented by mathematical content (e.g., which addend of a problem they started counting from, Geary et al., 2012) as opposed to delineating specifically by modality throughout the task. This methodological approach blurs any specific benefits of gestures in mathematical contexts. Thus, a model which centers domain-specific arithmetic knowledge, domain-general executive function abilities, and children's observable problem-solving behaviors like gestures is required to address the gaps in the current research regarding the interrelations between foundational math knowledge and cognitive capacities. In other words, understanding how individual differences in children's executive function abilities, arithmetic knowledge, and subsequent use of gesture strategies may help to address how each factor accounts for unique variance within children's problem-solving performance and contribute to learning success as children acquire more arithmetic content and develop their executive function abilities.

Answering these questions will help lay the groundwork for researchers to develop interventions to support children who may benefit from the use of gestures to boost mathematics performance on tasks (especially those problems higher cognitive demands) during early mathematics learning. Moreover, this line of inquiry is necessary given that students' mathematics performance on problems that require higher levels of cognitive processing is an issue of national concern. In 2012, the Organization for Economic Co-operation and Development ranked students in the United States as 27th out of the 34 participating countries on measures of general mathematics, noting that our students are particularly weak at solving "mathematics tasks with higher cognitive demand(s)" (OECD, 2013). Therefore, investigating the interrelations between children's foundational math knowledge, executive functions, and their subsequent use of gesture, a uniquely beneficial strategy for domain-general and -specific gains, may be essential to addressing this problem.

Study Rationale

Numerous studies have demonstrated a relation between children's mathematics ability and their executive function (for reviews, see Bull & Espy, 2006; Bull & Lee, 2014; Cragg & Gilmore, 2014; Jacob & Parkinson, 2015; Peng et al., 2016). Furthermore, the spontaneous use of gestures during math tasks has been linked to math knowledge (Gordon et al., 2019), as well as executive function, specifically indicated as a mechanism by which speakers may lighten their cognitive load (Goldin-Meadow et al., 2001; Wagner et al., 2004). These fundamental links were used to build a new theoretical model; the Gesture in Math Environments Model (GME model, Gordon & Ramani, 2021). The GME model provides a child-centered approach for researchers to consider how varying levels of domain-specific mathematics knowledge and domain-general executive function abilities contribute to observable behaviors such as gesture and verbal problem-solving responses and answers in math contexts. While working memory and attentional capabilities have been studied at length in terms of their relation to the use of gesture, the role of inhibitory control (also commonly referred to as "inhibition" in the literature) has been under-studied in empirical work related to children's mathematics and gesture.

Inhibitory control can be broadly defined as a set of cognitive processes which allow individuals to stop an impulsive or dominant response to select a more favorable, goal-directed behavior. This ability has been positively linked to math achievement (see Cragg & Gilmore, 2014 for a review). Here, Macleod's (2007) definition of inhibition may also be applied: "Cognitive inhibition is the stopping or overriding of a mental process, in whole or in part, with or without intention" (p. 5). This ability has been linked to children's math ability, given how inhibitory control reflects children's ability to inhibit incorrect mathematical strategies and dominant responses during problem solving (Borst et al., 2012; Linzarini et al., 2015). Therefore, the mechanistic role of inhibitory control can be further understood as the ability to ignore potentially misleading information or inhibit competing strategies based on previously learned procedural or factual information in lieu of a more appropriate strategy (e.g., Gómez et al., 2015; Lubin et al., 2013).

With numerous definitions relating to cognitive and mathematical understanding, representing the role of inhibitory control is challenging. A more concerted, developmental perspective summary is presented here: Children approach new mathematical content equipped with their prior knowledge and theories, each of which is a byproduct of their first-hand experiences from the world (Piaget, 1974). In order to successfully acquire this new concept, they must learn the associated factual material and undergo modification of their existing schemas to understand any procedural aspects going forward (Carey, 2009). Behaviorally, this could be recognized as a shift in problem-solving procedures, towards more efficient or cognitively complex mathematical strategies (Siegler & Araya, 2005; Siegler, 1996; Siegler & Shrager, 1984). Research suggests this shift is at least in part due to children's inhibitory control ability. Previous studies show that low inhibitory control levels correlates with lower math abilities (Bull et al., 1999; Bull & Scerif, 2001; St. Clair-Thompson & Gathercole, 2006). Additionally, evidence further suggests children with higher inhibitory control abilities show higher performance on word, algebra, and calculation problems (Agostino et al., 2010; Khng & Lee, 2009; Passolunghi & Siegel, 2001; Swanson, 2006). Thus, the explicitly observable strategies used during mathematical problem solving may be tangible and useful sources of information pertaining to children's inhibitory control.

Previous research has further implicated inhibitory control as an important factor in children's learning and performance for arithmetic specifically. While very young children can solve basic arithmetic operations related to addition and subtraction (Lubin et al., 2010; Wynn et al., 1992), additional work has shown that solving simple arithmetic problems also relies on their ability to inhibit prepotent or automatized responses information, which may be interfering with their ultimate expression of the most relevant mathematical strategy (Gilmore et al., 2015; Robinson & Dubé, 2013). Evidence suggests that children's inhibitory control ability has been shown to predict future success on measures of arithmetic above and beyond the effects of age, verbal abilities, and maternal education (Blair & Razza, 2007; Espy et al., 2004; Clark et al., 2010). This work extends to children as young as 3 years old, showing that inhibitory control is a unique contributor to their early arithmetic abilities above and beyond other factors (e.g., working memory and receptive vocabulary; Harvey & Miller, 2017). Collectively, this research underscores the importance of connecting children's inhibitory control abilities to their arithmetic learning. However, while children's propensity to enact a particular type of strategy (e.g., gesture-based finger counting) have been linked to differences in other cognitive and mathematical factors (e.g., working memory and cardinality; Gordon et al., 2021), there is not enough empirical evidence to outline if and how inhibitory control impacts arithmetic strategies in the same manner.

Thus, the comprehensive basis of the current study can be understood as the first step in evaluating a new, modified version of the GME model with the addition of inhibitory control. This adaptation is motivated in part by the National Mathematics Advisory Panel's (2008) report that children's learning will benefit greatly from a strong, early approach that focuses on the "mutually reinforcing benefits of conceptual understanding, procedural fluency, and automatic (i.e., quick and effortless) recall of facts". This message highlights how the role of inhibitory control may impact the beneficial potential of gestures during arithmetic contexts. First, gestures have been shown to boost conceptual understanding of mathematics (e.g., Broaders et al., 2007). Next, gestures can be used as a strategic representation of procedural information (e.g., finger counting; Siegler & Shrager, 1984). Lastly, children's repetitive use of more naive gesture and/or verbal strategies builds long-term memory connections may in turn allow for the use of more mental, retrieval-based strategies over time (Ashcraft, 1982; Siegler, 1996). Studies using brain imaging methods suggest that finger schemas may rely on the same neuroanatomical substrate as numerical processing (i.e., the parietal network; Pesenti et al., 2000; Pinel et al., 2004).

Moreover, studies have suggested that gestures may be the missing cognitive tool or link which allows for the building of connections between early math concepts, procedures, and facts for non-symbolic numerosities and symbolic arithmetic content (Andres et al., 2008; Fayol and Seron, 2005). Therefore, understanding the behavioral correlates related to children's strategic gesture use during arithmetic problem solving can provide insight into the design of future interventions focusing on the cognitive benefits of gesture.

The current study presents the requisite comprehensive analysis of the math and cognitive factors, specifically inhibitory control, and how each relates to children's use of gesture as a strategy during arithmetic problem solving. In previous work, children's arithmetic abilities have been indexed through observation of their problem-solving strategies ranging from explicitly observable gesture-based strategies, such as finger counting (Siegler, 1998), to memory-based strategies (e.g., retrieval from long term memory; Carpenter & Moser, 1984). Memory strategies are comparatively higher in cognitive demand as they require the individual to use only implicit, mental resources (e.g., connections between limited memory stores and knowledge stored within long-term memory; Geary et al., 2012). Conversely, gesture use during math tasks has been shown to reduce cognitive demand due to their embodied capacity to store relevant procedural or factual information on the fingers and hands during problem solving (Cook et al., 2012; Goldin-Meadow et al., 2001). Furthermore, children's use of gestures relates to their math knowledge, as well as components of more general cognitive capacities (Gordon et al., 2019; Gordon et al., 2021; Gordon et al. In Prep). In other words, children's gesture use as a strategy relates to their math procedural and content knowledge, as well as to their general cognitive skills like executive function. However, while gestures are broadly beneficial to math, our recent theoretical work outlined a critical gap in research regarding the interrelations between individual factors which could augment or diminish those beneficial effects (Gordon & Ramani, 2021). This prevents specific conclusions regarding whether gestures provide a differential benefit based on children's individual executive function and math abilities, which is prohibitive to later intervention efforts.

Study Design

The present study examined the relations between multiple *components* of children's executive function abilities, their domain-specific math knowledge, and their subsequent use of gesture on arithmetic problems. While prior research suggests that children's executive function, mathematics skills, and use of gesture as a strategy are linked (for a review, see Gordon & Ramani, 2021), there is a lack of empirical evidence investigating how inhibitory control and gesture relate. Specifically, the proposed study was the first to investigate how inhibitory control may be concurrently related to children's use of gestures during arithmetic problem solving through its connections to working memory (another part of executive function) and math abilities.

Children between the ages of 4.00 to 7.99 years completed two assessment sessions online and their parents/caregivers completed two online surveys. All child assessments were presented in an engaging, game-based format. Session 1 took place asynchronously on the virtual experiment platform, Gorilla, and included three measures; one assessing inhibitory control (Flanker Task), and two assessing children's early math abilities (Forced Choice Arithmetic Task, Magnitude Comparison Task). Session 2 was conducted with a live research assistant over the video conferencing platform, Zoom. This session included one measure of inhibitory control (Head Belly Task; adapted from Head Feet Task), one measure of children's arithmetic ability, where their use of gesture during problem solving was also assessed (Addition Strategy, adapted; Geary et al., 2004), and two measures of working memory (Forward and Backward Word

Spans). Parents were asked to submit the Digital Parent Behavior Rating Inventory of Executive Function® (BRIEF2 or BRIEF-P, depending on child's age) which provided additional scores of children's inhibitory control and working memory. Parents were also invited to submit an optional demographics questionnaire to collect additional data pertaining to the generalizability of the sample. Each of these parent and child level scores were standardized then considered in a series of models to investigate how each variable for inhibitory control, working memory, and math ability related to one another. Ultimately, the novel question of whether an interaction between children's inhibitory control and working memory abilities may predict children's gesture use during arithmetic problem solving was assessed.

Research Aims and Hypotheses

Broadly, the goal of the proposed study was to assess how children's inhibitory control related to their use of gesture strategies in mathematical contexts. The established GME model provided a framework by outlining which additional factors (beyond inhibitory control) should be considered to address this question; namely children's working memory, math abilities, and age. Thus, the following hypotheses and aims were constructed to investigate a new version of the GME model, wherein the interactive function of inhibitory control with working memory was tested.

Aim 1: To determine how children's inhibitory control, working memory, math, and gesture use varies by children's age and gender. Based on prior work, age was expected to positively relate to working memory (e.g., Gathercole et al., 2004) as well as math (e.g., Geary 1994). However, a negative trend between gesture and age was expected due to the general trend in math contexts where children's use of gesture strategies decreases as their use of more efficient and sophisticated strategies increases (e.g., retrieval; Ashcraft, 1982; Siegler, 1996).

Recent work focused on children's gestures in arithmetic contexts specifically showed that children's age was negatively correlated to their use of gestures strategies but positively correlated to the use of mental-based strategies. (e.g., Barkin & Ramani, under review). The current study expands upon the unique considerations regarding how developmental and social influences such as age and gender can be considered. Additional consideration regarding the prevalence of any gender effects in the predictors and outcome were assessed. Further discussion of the presence of gender differences for gesture use is warranted. The next aim considers how inhibitory control and working memory may concurrently relate to each other and predict gestures above and beyond the impacts of age and gender.

Aim 2: To examine how children's concurrent inhibitory control, working memory, math, and use of gesture strategies are related, accounting for age and gender. While each of the predictions outlined in Aim 1 follow expected paths within previous research, questions pertaining to the concurrent relations of inhibitory control, working memory, and math knowledge and how each may relate to gestures in different ways depending on children's age level are more complex. Prior research suggests that the assessment of these connections could be difficult, due to a potentially delicate relation between inhibitory control and math generally as children get older (Cragg & Gilmore, 2014). Moreover, prior work has shown that examining the relations between individuals' use of gesture and their working memory capacity or age can be tenuous depending on each child's current developmental stage (e.g., Gordon et al., 2021; Marstaller & Burianová, 2013). Given the tight inter-relations found between each predictor and the rapid development of working memory, inhibitory control, and math knowledge that co-occur within the selected age range (4.0-7.9 years), it is necessary to quantify how these relations may vary at different developmental stages.

The current study used structural equation modeling to assess the relations between measured variables and potential latent factor structures with the sample data. A model including a broad executive function factor indicated by all measures of inhibitory control and working memory were compared against a two-factor model where these measures loaded onto separate factors. After assessment of fit indices and theoretical considerations, further analyses were conducted on the two-factor model (e.g., separate factors for inhibitory control and working memory). Using this structural model as a base, a regression was added next wherein children's working memory and math knowledge predicted gesture, while accounting for variance in inhibitory control, age, and gender. This regression was based on evidence from prior studies children's strategy use where gesture strategies appear more for younger children given that they are more likely to lack additional relevant procedural knowledge, whereas for older children a tradeoff is expected to occur towards more efficient and complex strategies (Shrager & Siegler, 1998). Additionally, this regression was driven by evidence supporting that age is not the primary source of expected variation in gestures; for example, while older children are found to use gestures, research suggests that this use of a gesture strategy is representative of backtracking to a previously learned strategy in the face of problem demands (Overlapping-Waves Model, Siegler, 1996). Thus, in this instance, the observation of an older child using gesture is more likely attributable to a lack of working memory resources, such that gesture is a particularly useful strategy given its ability to lighten the cognitive load (e.g., Goldin-Meadow et al., 2001; Wagner et al., 2004).

Additional support for age as a covariate within these analyses come from evidence showing that children beginning to learn arithmetic employ counting strategies (either with or without gesture; Fuson, 1982; Groen & Parkman, 1972). Over time and with practice, children develop memory representations of associated mathematical facts and procedures that were used during the foundational practice of counting (e.g., memory-based processes such as direct retrieval, decomposition of problems, etc.; Siegler & Shrager, 1984). Thus, growth can be observed in the child's use of more advanced strategies where they begin to recall these facts from memory or decompose components of the addends verbally to provide a solution (Geary et al., 1992; Siegler, 1987). Therefore, older children with low levels of inhibitory control may still fail to inhibit a prepotent response, the expected observed behavioral result would be tied to a memory or verbal-based strategy.

At the center of children's attempt to problem solve, there is the possibility that they may employ gestures. To fully consider what mechanisms drive the use of this beneficial strategy, we explored how an interaction between inhibitory control and working memory could represent the specific procedural and factual knowledge children would rely on for arithmetic problem solving. Thus, the final question of how mathematical knowledge may be drawn on or inhibited during a problem-solving context, leading to differential use of gestures for children of different ages is explored in Aim 3.

Aim 3: To test the role of inhibitory control as a moderator of the relation between children's working memory abilities and gesture use during arithmetic problem solving. The current study expands upon the various connections within prior research associating children's early mathematical skills, executive function abilities, and their use of gestures (for a review, see Gordon & Ramani, 2021). Using the GME model as a foundation (Figure 1), the final aim of the current study is to determine the role of inhibitory control as a moderator on working memory as it pertains to the outcome of children's gestures in arithmetic problem solving. This hypothesis is based on the theoretical and empirical proposition that inhibitory control acts as a gating mechanism, whereby children's inhibitory control levels do (or do not) change the directional flow of information being processed within working memory (Morrison et al., 2011). This account is further supported by the idea that the processing of information can be changed in part based on better attentional control and slower decay of information (e.g., Cowan et al., 2002). Empirical evidence also supports the addition of math ability as a predictor of children's gestures, even when controlling for age (e.g., Gordon et al., 2019; Gordon et al., 2021). Thus, the primary working hypothesis is that inhibitory control plays a moderating role in the relation between children's working memory and their subsequent use of gestures during arithmetic problem solving.

To test this new version of the GME model (Figure 2), structural equation modeling following the confirmed structural model (outlined in Aim 2) were performed. Specifically, this model included main effects of children's working memory abilities and an interaction between inhibitory control and working memory predicted gesture. Here, children's age, gender, and inhibitory control ability were retained as covariates to gesture use. It was predicted that a significant interaction effect between inhibitory control and working memory would be found, confirming the moderating effect of inhibitory control.

Contribution to the Field

The proposed study was one of the first to investigate the simultaneous relations between children's inhibitory control and use of gesture during arithmetic problem solving from a developmental perspective. The age range of participants spans a period when both arithmetic skills and executive function are undergoing rapid improvement, in turn leading to a wide variety of ability levels and variation in gesture strategy use. The proposed analyses allowed for testing of the relations represented in the novel the GME model, accounting for each individual level factor that is implicated by children's use of gesture. This study laid the groundwork for future empirical and applied work alike by testing the hypothesized relations of children's domain-specific mathematics skills and executive functioning skills regarding their use of gesture. As such, this work provides future researchers with a more holistic, fully represented model. Once the connections between inhibitory control and gesture are addressed, additional work pertaining to the manipulation of gesture to influence each factor may be examined. Results from the current study can thus be used in the future to provide insight on the role of children's inhibitory control as it relates to children's use of gesture in mathematical contexts.

Chapter 2: Review of the literature

Overview

This review provides a summation of the research regarding relations between children's arithmetic knowledge, executive function abilities, and hand gesture use. It begins with a discussion regarding how children's use of and exposure to hand gestures can shape their learning, general theories of gesture and mathematical problem solving, as well as a synopsis regarding the establishment of the GME theoretical framework (Gordon & Ramani, 2021). Within this first section, additional background information is provided on two important, but separate theories; the information processing approach and the theory of embodied cognition. Following the explanation of the GME model, the next section includes a review of relevant literature regarding the trajectory of early mathematical development with a focus on arithmetic as well as a discussion of how these results may be interpreted within the proposed model. Within this overview, the roles of crucial executive function skills are discussed as potential predictors both in early school years and beyond. Additionally, additional discussions regarding empirical findings related to gestures and executive function outside of mathematics contexts are considered, to fully capture the breadth of research that may apply to the cognitive benefits of gesture during math contexts. Each of these will be discussed in terms of how this research informs the GME model.

The next section highlights the notable lack of empirical work related to inhibitory control, math, and gesture. Thus, to consider these potential relations of inhibitory control, as well as make informed predictions based on relevant literature, and eventually add to the GME model, two separate bodies of work are reviewed. First, a summary of the various existing terminologies and definitions of inhibition are covered, followed by a distinctive outline of the current definition of inhibitory control for the current study. Next, the relations between inhibitory control and children's early mathematics problem solving and learning are reviewed. Additionally, common measures used to assess children's inhibitory control are summarized.

Finally, the concluding section provides a detailed discussion regarding a prominent gap in the literature, the relation between inhibition, mathematics, and gesture use. This collective review of separate domains thus allows for more holistically informed predictions in the present study, as well as the potential to address any remaining gaps within the literature to demonstrate how a new version of the GME model, once inhibitory control can be added, will lay a foundation for future research to examine the mechanistic role that gesture may play in children's math learning.

A Framework for Gestures Use in Math Environments

Gestures are dynamic hand and body movements that accompany language. They can occur spontaneously or intentionally and oftentimes provide different yet complementary information to a person's speech (Church & Goldin-Meadow, 1986; McNeill, 1992; Church, 1999). A speaker's gestures can facilitate the listener's comprehension (for a meta-analysis, see Hostetter, 2011) and improve overall communication compared to speech alone (Church et al., 2000). Therefore, the information provided by speakers' gestures is useful to those who see them.

Self-produced gestures can serve an important, internal purpose for the user as well. Hand gestures allow a speaker to simultaneously process their thoughts and put them into communicative form (Krauss, 1998; McNeill, 1992). People continue to gesture even when no one is watching (Alibali et al., 2001; Krauss et al., 1995). Research has shown that congenitally blind speakers use gestures even when they are communicating with a blind listener (Iverson & Goldin-Meadow, 1998), suggesting even those who have never seen gestures modeled in communication will use them too. Thus, gestures appear to support internal mechanisms of communication and cognition.

One environment where gestures are uniquely beneficial for both children is during mathematical contexts. Children use gestures to represent mathematical information, enhance conversation, and even support their own cognition (for a review, see Goldin-Meadow, 2009). Their self-produced gestures during problem solving or explanations (e.g., Broaders et al., 2007; Cook et al., 2008), as well as the gestures they see teachers use during math instruction (e.g., Singer & Goldin-Meadow, 2005), have been shown to support their learning. Given that children’s early math knowledge has been consistently linked with their later math achievement (Claesens & Engel, 2013; Geary et al., 2013; Geary & Vanmarle, 2016; Watts et al., 2014), factors related to children's math understanding, like gesture, are important to understand.

One mechanism by which gesture is said to support mathematical learning is through its ability to aid cognition (Cook et al., 2012; Goldin-Meadow et al., 2001). Specifically, gestures can be linked to different components of domain-general abilities, such as executive function. Executive function refers to the cognitive control processes that coordinate sub-processes such as attention shifting, working memory, and inhibitory control (e.g., Bull and Lee, 2014). Given the association between children's executive function and math abilities (see Clements et al., 2016 for a review), as well as gestures supporting math through executive function, here it is proposed that it is important to study these factors together.

Due to the prevalence of gestures across ages, contexts, and domains, numerous theoretical models have been created to account for their communicative and cognitive functions. Each theory understandably overlaps in part with another; however, each one also provides complementary information explaining new contexts, factors, and functions. For example, frameworks that focus on what can be uncovered about a speaker's cognition (Goldin-Meadow, 2003), or where gestures emerge from (Gesture as Simulated Action framework, GSA; Hostetter & Alibali, 2008) both provide insight into how gestures relate to and shape underlying cognitive processes. Furthermore, the GSA framework builds upon another foundational idea that these cognitive processes are rooted within the environment (embodied cognition, Barsalou, 1999). Gestures have also previously been considered under theories of cognition, such as Cognitive Load Theory (Sweller, 1988). This framework provides an explanation that self-produced gestures reduce "cognitive load", a mechanism that is often considered as one of the main roles of gestures. Each of these, as well as other gesture-related frameworks, provide unique and compelling explanations of the distinctive roles of gestures as they relate to a particular set of circumstances. However, these models do not consider the specific role of gestures in mathematical contexts. Here, the goal was to create a model based on the growing literature regarding the benefits of gestures during math environments.

Additional frameworks from the mathematical literature can partially address the mathematical context, as well as categorize gesture as a strategic behavior that children may or may not use. For example, the Overlapping-Waves Model (Siegler, 1996), portrays growth in math knowledge across development as a representation of flexible shifting from one math strategy to another. Over time, children build upon a foundation of basic strategies, adding more complex approaches to their repertoire. From this perspective, young children use multiple strategies from gesture and verbal modalities across time until they develop the fundamental abilities necessary for more advanced, mental strategies. As time goes on, these new strategies are used more frequently while the verbal and gestural strategies taper off, but they are still able to revert to more naive strategies if needed. However, this conceptualization of strategy use within is missing key information regarding the role of children's general cognitive abilities.

Therefore, the processes by which children select specific arithmetic strategies during problem solving have been further specified in computational frameworks (e.g., Siegler & Shrager, 1984) and mental models (e.g., Huttenlocher et al., 1994). These conceptualizations were further detailed to include working memory as an underlying heuristic involved in children's strategy use (e.g., metacognitive system within SCADS Model; Shrager & Siegler, 1998). While these models do suggest that gestures may have a function, noting that children may use their fingers to represent some of the numerical or procedural information related to the ongoing mental processes (e.g., Siegler & Shrager, 1984), the multitude of research which stems from models such as these gloss over the unique contributions which gestures can provide.

Thus, the literature is best supported by a model that integrates two previously established frameworks. First is the information processing approach, commonly used within math research to represent how information moves through each component of human cognition during problem solving and learning. Second is the theory of embodied cognition, the basis of many gesture theories. This framework provides the GME model's infrastructure, as it articulates the importance of human cognition being situated within a body, further encompassed in an active, stimuli-ridden environment.

Information Processing Approach

One way to conceptualize how children solve math problems and learn math-related content is the Information Processing approach (e.g., Pellegrino & Goldman, 1987). This is not a single theory, rather an umbrella term for approaches that explain human cognition as a system that processes stimuli input from the environment and delivers a variety of outputs. The Information Processing model suggests that learning occurs via a flow of information through a series of memory stores and processes, each of which could be further conceptualized as the subcomponents of executive function (adapted from Lutz & Huitt, 2003). Input is received from stimuli in the environment by way of the sensory registry. Attention is directed to fixate on relevant information, which progresses to working memory, a short-term store where information is held and processed for use in further cognitive tasks (Gathercole, 1998). Working memory is responsible for determining what information is important, choosing and enacting problem-solving strategies, and coming to a solution. Ultimately, information will either be forgotten or encoded and stored in long-term memory for retrieval later.

Although the Information Processing framework can be broadly applied to represent children's math problem solving and learning, there are ways in which it could be further specified. First, a framework that focuses on both visual and auditory math-specific input could help to better understand how this input is relevant for children's math abilities and learning. Second, when investigating the role of gesture in children's early mathematics, a framework needs to include the body itself. While the Information Processing model describes the cognitive processes, it does not explain any co-occurring physical behaviors. Thus, this framework cannot adequately account for the gesture-specific benefits that may occur within a math-related context. The question remains open as to how to model the role of the learner's body, and the different types of math stimuli (words and gestures) within the environment.

Embodied Cognition

One theory that provides insight into these two components is embodied cognition. While embodied cognition has been conceptualized in various ways, each adaptation generally emphasizes the body and stimuli within the surrounding environment as important to cognition (e.g., Barsalou, 1999; Clark, 1999; Shapiro, 2019). Wilson's (2002) presentation of embodied cognition specifically conveys six central claims of embodied cognition, three of which outline the importance of considering cognition as a situated process, and the other three focus on the importance of the body as a tool for cognition.

The first claim stipulates that cognition is situated. In other words, cognitive processing occurs in parallel with the task-relevant inputs and outputs from the environment. Thus, cognition cannot be separated from an interplay between the perception of the environment and subsequent actions taken. The second claim is that cognition is "time pressured," where cognitive processing requires real-time responses to the stimuli in their environment. Lastly, Wilson's fourth claim states that the environment is an important part of the cognitive system. While similar to the first claim, Wilson outlines that since the reception of stimuli, cognitive processes, and behavioral responses are cyclical in nature, each of these components cannot be considered alone.

Wilson's claims three, five, and six all focus on the role of the individual's body in cognition. Claim three emphasizes that humans tend to off-load cognitive work externally in strategic ways. Wilson provides finger counting as an example, indicating this gesture can be used as a representation of relevant numeric information (e.g., linking number words to objects to keep track of quantity). Thus, offloading is a critical cognitive function that helps the speaker reason and express thoughts. The fifth claim states that cognition's primary function is for action. Meaning, a person's perception of the world as well as their concepts and memory are both “for” and “formulated by” their behaviors. Lastly, claim six says that off-line cognition is “body-based.” Wilson's conceptualization of off-line cognitive processes involves any that are separable from the time-sensitive environment. Importantly, though they are distinct from the environment itself, the processes within the mind are inevitably tied to cognitive mechanisms that were originally designed for external behaviors, such as sensory processing and motor control.

The critical takeaway from Wilson's presentation of embodied cognition is that both the body and environment are integral to cognition. Her representation of embodied cognition underscores how embodied practices can result in an offloading of cognitive load. Based on this important contribution of the body and the environment, and a focus on how cognition may be offloaded, a new model combining central tenets from both Information Processing and embodied cognition was recently proposed (GME model; Gordon & Ramani, 2021).

The Gesture in Mathematics Environments Model (GME model)

GME model contains aspects from embodied cognition and Information Processing and specific contextual elements of gestures within the mathematical environment (Figure 1). This new model is unique in its applicability to different math domains. For example, during a lesson on addition, math input could include a teacher's speech and gestures in reference to an equation on the chalkboard, while the output could be children's verbal and gestural responses and explanations. In another context where a younger child is counting a set of objects, their math input could be instructions and countable objects, and their output may include them pointing and counting out loud. Thus, there are numerous opportunities for applying the model for research by specifying the components (learner, input, and output) within a math environment.

Notably, this model also does not differentiate between perceived speech and gestures. Instead, it includes a unified representation of math input. This combined representation is based on research showing that simultaneous presentation of these two observed modalities can be beneficial for children (Congdon et al., 2017). However, children's math output is differentiated in the model because the literature (reviewed in subsequent sections) suggests children's gestures and speech often contain different but complementary information. For example, recent work supports the separation of math output by modality, given that temporal-synchrony of self-produced gestures and speech does not relate to learning and retention for children in the same way that observed gestures do (Wakefield et al., 2021).

Incorporating gesture as input and output separately allows the model to be adapted in two critical ways. First, it can be applied to different mathematical domains (e.g., cardinality, algebra, fractions, etc.), such that the input and output can vary by content. Second, the model can be used to understand a broad range of differences in children's general executive function abilities and math knowledge specifically. This is of particular importance given children are found to be adaptive in their responses to math problems (Siegler, 1996), and that the strategies children display may differ between their speech and gesture (Goldin-Meadow et al., 1993).

Consider the example of a child solving the problem 3+2; if they have the answer memorized, they may quickly answer “5!” using a direct retrieval strategy of relevant math knowledge. A second child, who has only learned about arithmetic principles generally, would likely respond differently to the same problem. They may use a backup strategy (i.e., any method other than retrieval), such as holding up three fingers then extending two more while counting on “4…5! The answer is 5.” The proposed model highlights how these children's individual differences in math knowledge could impact their use of self-produced gestures and would allow researchers to explore the theoretical implications of how these strategies connect to their subsequent math abilities and later learning.

In addition to understanding the connection to math knowledge, an additional goal of the proposed model is to explain how gestures may be beneficial for executive function and its subcomponents. Executive function includes three separate, but interrelated processes; attention shifting, inhibitory control, and working memory (Miyake et al., 2000). While executive function is often discussed as a multidimensional construct, there is also evidence of unidimensionality in early childhood (Wiebe et al., 2008; Hughes et al., 2010). This makes it difficult to determine empirically whether the benefits of gesture for children relate to executive function broadly or one specific sub-component. For example, it is common within the gesture literature to discuss gestures as providing a reduction in “cognitive load” (Goldin-Meadow et al., 2001) or linking them to executive function broadly (O'Neill & Miller, 2013). As such, connections between sub-components of executive function and gesture are represented in the current review based on how they are discussed within their respective studies. The implications of this approach are reviewed in the discussion.

In sum, when studying the role of gesture in math environments, the GME model acts as a combined model of the Information Processing approach and theory of embodied cognition. By establishing the pattern of information processing flow within specific embodied locales and conventions of embodied cognition, this new model provides a dynamic representation of the cognitive impact of gestures in a mathematical environment. The connections between children's domain-specific knowledge (stored in long-term memory) to their self-produced gestures are illustrated within the model itself, as is an additional pathway between math input and children's

EF. Thus, both types of gestures relate to children's cognition. Given this model, it is now possible to consider the specific role gestures play in mathematical contexts.

Gestures in Math Environments

In this section, literature on two types of gestures included in the GME model is reviewed. First, a review of the literature about gestures used by other people, such as a teacher or experimenter, to explain or teach math concepts is included in the model's “Math Input” section. Second, literature regarding children's self-produced gestures is reviewed; included in the model's “Math Output” section. Studies in these areas establish two critical functions (represented by connected arrows in Figure 1). One function highlights how children's self-produced gesture may convey math information (stored within their memory), which assists with their cognitive processing (executive function abilities). A second connection between children's gesture math-output connects back to their math input, which allows for the possibility that children's gestures elicit math information from their environment. Each of these functions is reviewed and discussed.

Math Input: Observing Other People's Gestures

Individuals who observe a speaker's gestures during a mathematical context can extract useful information (Alibali et al., 1997; Goldin-Meadow et al., 1992; Kelly & Church, 1998). No training is required to gather this information, as children are readily able to attend to information found uniquely in gestures (Kelly & Church, 1997). Therefore, gestures that occur within math environments are straightforward in their presentation yet are critical to understand.

Experimental studies have shown that watching gestures can support the learning and generalization of math concepts. For example, Graham (1999) had 2–4-year-old children (n = 85) watch a puppet point while counting objects. When asked about the puppet's performance, children spoke about the puppet's gestures suggesting that from a young age, children are explicitly able to recognize gesture strategies (pointing) in a math environment. Alibali and DiRusso (1999) used a similar paradigm with preschoolers (n = 20; M_{age} = 4.67), where a subset of children was asked to count aloud while watching a puppet gesture to keep track of the objects. These children made fewer counting errors compared to children who had no gesture supports (either their own or the puppets). These studies illustrate how young children can benefit from receiving gestures as part of their math input.

Research has also examined how gesture input could benefit other domains of math. Valenzeno et al. (2003) worked with 25 preschool-age children (M_{age} = 4.5 years) who watched videos of teachers providing instruction on symmetry in a speech alone, or in gesture plus speech. Children who saw the gesture plus speech instructions had higher posttest scores for this math concept, compared to children who received instruction in speech alone. Thus, children who received math input with gestures showed greater improvement in math knowledge compared to their peers who received speech alone.

Additionally, children are also able to detect information that is uniquely communicated through gestural math input. Specifically, Goldin-Meadow et al. (1999) asked a group of teachers to give children (n = 49, M_{age} = 9.83 years) lessons on mathematical equivalence1. Teachers were not specifically told to gesture, though they did gesture spontaneously during instruction. These gestures contained relevant problem-solving strategies, such as a v-handshape to group two numbers visually that should be summed or gesticulating a flat palm under one side of a problem and then the other to indicate equality. These gestures either reinforced the information in the teacher's speech (gesture-speech match) or contained different, but complementary information (gesture-speech mismatch). Overall, children were more likely to reiterate their teacher's speech if it was accompanied by a gesture. Critically, children were also found to be able to recognize information that was solely presented within a teacher's gesture. This suggests that children both notice and process the mathematical information presented uniquely by gestures.

Children's ability to perceive information from gestures is further supported by evidence from a bilingual sample (Church et al., 2004). In this study, 51 Spanish-speaking first-grade students (Mage = 7.0 years) were assigned either to a Spanish-speaking classroom in the school or to an English-speaking classroom. Students watched a video of an English-speaking teacher providing instructions either with or without gestures. These gestures were gesture-speech mismatches, such that they contained unique but complementary information to speech. Overall, children in both classrooms benefited from the inclusion of gestures during instruction, and Spanish-speaking children's learning increased from 0 to 50%. This suggests an additional benefit of including gestures as math input. Specifically, gestures may be a more universally accessible representation of math information, as its manual format is not tied to a language.

Singer and Goldin-Meadow (2005) continued to build off this line of inquiry using the mathematical equivalence paradigm. Specifically, 3rd and 4th-grade children (n = 160) were taught problem-solving strategies either with no gesture, gesture-speech matches, or gesture-speech mismatches. Children were more likely to learn when their teacher's math input contained one problem-solving strategy in speech, while simultaneously presenting a different strategy in gesture. This finding extends previous work by suggesting that the addition of gesture to speech is unique in its ability to present two math concepts simultaneously (one in each modality), which in turn facilitates learning. Therefore, the inclusion of gestures as an accessible, beneficial form of math input is cemented in the model.

It is additionally important to review research on how gesture input may impact children's math knowledge. Cook et al. (2013) asked 7–10-year-old children (*n* = 184) to watch a video where an instructor provided a lesson on math equivalence either with or without gestures. Children completed both an immediate and delayed posttest to test for general learning and transfer. Compared to children who received instruction in speech alone, children who received gestural math input performed better on both the immediate and later posttests, including a transfer of knowledge to new problems. Thus, children appear to gain and generalize knowledge quicker when the relevant information is provided with supporting gestures, as opposed to speech alone. These findings provide insight into how the inclusion of gestural math input could impact children's math output, such as their response to a later math test.

Additional work expanded on these results with a computerized avatar (Cook et al., 2017). Sixty-five children (M age = 9.0) watched as a computer avatar provided instruction on mathematical equivalence, either with or without accompanying gestures. Children who saw the gesturing avatar learned more, solved problems quicker, and were more likely to generalize their knowledge. Thus, children benefited from the addition of gestures regardless of whether their instructor was a human or a computer avatar. These results reveal how gestural math input can be expanded to include technology-based instruction to advance children's learning and generalization of knowledge. This emphasizes the connections within the proposed model regarding math input to children's overall math understanding.

Together, these findings suggest that children notice, and process mathematical information provided in the instructor's gesture. These gestures are found to enhance children's learning and support broader understanding through concept transfer and generalization. This literature is consistent with the proposed model; children receive math input from their instructor's gestures and speech, which supports their problem solving and later learning in the form of math output.

However, it is also critical to understand the mechanisms by which gestures provide these supports. One study assessed this issue by manipulating whether task-objects were in view, and thus referenceable, by their subjects (Ping & Goldin-Meadow, 2008). Specifically, kindergarten and first-grade students (n = 61, 5–7 years old) participated in Piagetian conservation tasks where they were shown two objects (e.g., two glasses with equal liquid) and were asked if they were equal. One of the objects was manipulated, (e.g., poured into a shorter glass), such that children's understanding of conservation could be assessed when asked to explain if they were equal now. Children then received instruction on conservation, either in speech alone or gesture-plus-speech, as well as either with or without the objects present. On average, children were more likely to learn from instruction that contained gesture-plus-speech, even when the objects themselves were not present. In other words, gestural math input was helpful beyond the scope of referencing specific, concrete objects within children's environments. Thus, the function of gesture as math input goes beyond simple attention direction or grounding of speech in the physical environment and has broader implications for children's learning.

Overall, the literature suggests that the gestures which children observe as math input can directly support their math learning, which reinforces these connections in the proposed model. Children are better able to learn, retain, and generalize new information about math when their instructor uses both gestures and speech, compared to speech alone. When children cannot access math information in their teacher's speech, gestures become even more important. These benefits extend beyond a simple direction of attention, as gestures continue to be beneficial even when the relevant items are not present.

Math Output: Children's Self-Produced Gestures

The following section includes literature on the self-produced gestures children use in math contexts to scaffold their knowledge and learning. These gestures occur spontaneously (e.g., Crowder & Newman, 1993) or because of explicit instruction (e.g., Alibali & Goldin-Meadow, 1993). In the proposed model, children's gestures are linked to supporting their ongoing cognitive functions, while also producing a form of math output. This output can then be observed by teachers to continue to inform the child's math environment (e.g., Gibson et al., 2019). Each of these functions of children's self-produced gestures is examined in turn.

Self-produced gestures have been shown to reduce cognitive load during math contexts. This benefit of gesture was examined by Goldin-Meadow et al. (2001), who asked participants to solve and explain age-appropriate math problems (e.g., math equivalence problems for children, harder problems for adults). They were also asked to remember a string of letters or words while explaining their solution. Gestures were manipulated directly, such that participants were instructed whether gestures were permitted, or if they should keep their hands on the table. Both adults and children were able to remember significantly more of their list when they used gestures during their math explanations. This finding supports the inclusion of children's self-produced gestures within the model. Furthermore, the authors suggest that the observed cognitive benefit may be due in part to gestures' utility in reducing memory demands, which may additionally link self-produced gestures to the memory processes in children's minds. Thus, this study is discussed briefly a second time in relation to working memory.

Another study investigated how self-produced gestures may further support children's performance on a math task. Specifically, Gordon et al. (2019) investigated how preschool children's own gestures may support their knowledge and performance on a cardinality task.

Results indicated that children's cardinality knowledge was positively related to their spontaneous gesture use, even while controlling for age. This relation was not just driven by children who had mastered cardinality; indeed, the same positive relation between gesture and cardinality knowledge existed for the subsample of children who were still learning principles of cardinality. Children were also found to gesture the most during parts of the task that were most difficult for them, subjectively, based on their current cardinality knowledge. This emphasizes the connection in the model between children's gestures, their math knowledge in long-term memory, facilitated by the problem-solving abilities within other components of EF.

Based on the advantages of self-produced gestures, additional work considers how providing explicit gesture instruction or encouragement to children may impact their performance or learning in math environments. Broaders et al. (2007) examined this phenomenon in two studies with 3rd and 4th-grade children who were asked to solve math equivalence problems. In the first study, children were asked to explain their solutions to these problems either using gestures, specifically without any gesture or heard no mention of gesture. Children who were told to gesture conveyed different information in this modality (i.e., gesture-speech mismatch), such that their math output contained new and relevant information. Therefore, instructing the use of gestures can lead children to express math knowledge with their hands that may not otherwise be communicated with their speech. The authors also sought to address whether children who received this instruction would be more receptive to learning by testing a new set of 3rd and 4th graders using a similar protocol for their second study. Results indicated that instructing children to use gestures not only taps into their implicit math knowledge but also makes them more likely to learn. Taken together, these results highlight how a combination of direct instruction (math-input), and the resulting self-produced gesture (math-output) could impact later math learning; the overall goal of the proposed model.

To further parse apart the benefits of instructed gestures, Goldin-Meadow et al. (2009) investigated whether specific types of gestures were more advantageous than others. Third and fourth graders completed math equivalence problems and were assigned to one of three training groups: no-gesture, correct-gesture, or partially correct gesture. Overall, children learned more when any gesture was used, regardless of whether the information it contained was mathematically correct. However, children who received correct-gesture training solved more problems correctly compared to the partially correct gesture group. This suggests that gestures which contain specific, correct math information are superior to other gestural types. Furthermore, children were able to verbalize the grouping strategy used in gestures without any direct instruction, indicating that children learned a strategy from their own gestures. Taken together, these results indicate that while any gesture may benefit children, instructing specific gestures that align with math concepts could allow children to extract and learn that information. This further supports the proposed model; children's self-produced gestures, while labeled as a form of "math-output," have connections to and from the knowledge storage and executive function processes within their minds. Thus, by providing instruction to children to self-produce a specific type of gesture, they may be able to tap into and build on task-relevant knowledge.

New research involving fMRI methods builds on the mounting evidence that providing instruction to children to use gestures improves their mathematics ability. Wakefield et al. (2019) worked with 7–9-year-old children who had engaged in the same mathematical equivalence training outlined in previous research (Cook et al., 2008; Goldin-Meadow et al., 2009). Children solved a series of these problems, then received training to express an equalizer strategy in either speech alone or speech plus gesture. Only children who had gotten all problems wrong initially then successfully solved at least half the problems after training were included in the final sample (*n* = 20). A week later, this sub-sample of children completed a short training refresher before participating in an fMRI session where they solved new mathematical equivalence problems. Results showed differences in neural activation during problem solving by training condition, such that children in the speech and gesture condition had greater activation of the motor regions of their brains compared to speech-alone. This indicates that training math concepts through self-produced gestures may have lasting neural impacts, even though children were unable to use gestures during the fMRI reading itself. Thus, the neurological research is consistent in its support for the pathways generated by the behavioral research for the proposed model.

However, it is essential to address whether these benefits are unique to gesture, or if any movement or action could render the same benefits. For example, could children use a bodily strategy consisting solely of actions and have the same mathematical benefits? Novack et al. (2014) explored this idea with 3rd-grade children using the math equivalence paradigm. Children were taught to use either a physical action on objects, a concrete gesture that mimicked that action, or an abstract gesture while solving the problem. While each of these strategies lead to more learning, only children who used gestures were able to generalize their knowledge to successfully complete later problems. Therefore, given that it is gestures rather than physical action that best assists learning and knowledge transfer, the current model provides a unique vantage point to delve further into how gesture confers these benefits.

Building off this line of work, Congdon et al. (2018) investigated how individual differences in children's math knowledge influenced their learning from gesture or action strategies. First-grade children's initial measurement knowledge was assessed, after which they received one of four trainings for a measurement task. Half of the conditions used a physical stick above a ruler aligned with zero, the other half shifted over to align with a different whole number. Conditions were further split by action or gesture-based trainings; Action-based training with physical manipulatives to show children how the ruler segments could be used to count, and gesture-based training using a "pinching" gesture to highlight the relevant segments of the ruler. Children who used simpler strategies incorrectly during the initial measurement assessment benefited from the action training, but not the gesture training. However, children who initially used a more complex, but incorrect, strategy at pretest learned from both the training with actions and gestures. This finding highlights the importance of recognizing how and when gestures could be applied, as well as how individual differences in children's math knowledge may influence the benefits of gesture. Encouraging the use of gestures may help a child who has reached a particular level of underlying math knowledge yet hinder another less-advanced child at the same time. Thus, our model centralizes the importance of gesture while also highlighting the importance of not separating the utility of the tool from its intended user.

In educational settings, it is also important to understand how children's self-produced gestures can provide information to an observer, and how this observer could provide additional math-relevant input. In their seminal work, Church and Goldin-Meadow (1986) examined 5–8-year-old children's speech-gesture mismatches to investigate whether these movements indexed their transitional knowledge. In the first study (n = 28), children participated in a series of Piagetian conservation tasks where an experimenter made visual transformations of two equivalent objects. Throughout the task, children were asked if the objects had the same amount and to explain the transformation. Children were categorized as a conserver (e.g., recognized the key concept of conservation), partial conserver, or non-conserver based on their explanations.

Children's speech and gesture use were coded during their explanation to determine if they were a match or a mismatch. On average, children who had more mismatches showed more complex knowledge in their gestures than their speech. Based on this finding, the authors conducted a second study where half of the children received direct instruction on the concept of equivalence while the other half were allowed to physically manipulate the objects. Children who had more speech-gesture mismatches in their explanations were more likely to learn new information after training and benefited from the opportunity to play and manipulate the objects afterward. In contrast, those children with more matches than mismatches did not show any additional benefits from explicit training or more informal contact with the objects.

These findings were further expanded upon by Perry et al. (1988), who sought to explore how spontaneous self-produced gestures used in math contexts could index children's “readiness” to learn new information. In a series of studies, they asked 9–12-year-old children to solve problems and explain their solutions related to concepts of mathematical equivalence and Piagetian conservation. In general, children's speech and gestures were more likely to match during the conceptually easier mathematical task (conservation), but more likely to mismatch during the more difficult mathematical task (mathematical equivalence). Additionally, the amount and the type of mismatches produced by children provided an index of their “readiness” to learn. Specifically, the authors suggest that children's math output (gesture and speech) provides insight into their math knowledge, as well as whether they may be able to receive new math input from their environment. Indeed, children's gesture and speech mismatches have been linked to their zone of proximal development (Goldin-Meadow et al., 1993a). In other words, their gestures may be used by adults to specifically calibrate future math input to a child's level of understanding.

To further understand how children's self-produced gestures mark their conceptual knowledge, Garber et al. (1998) assessed the speech gesture mismatches produced by 4th-grade children in their explanations of mathematical equivalence problems. Children subsequently were asked to judge the acceptability of a variety of other commonly used problem-solving strategies, some of which were incorrect. Overall, children gave the highest rating to strategies that contained conceptual elements that they had only indicated in their gestures during their initial explanations of how to solve equivalence problems. Thus, these children not only expressed knowledge uniquely in their gestures, but this knowledge was accessible when presented to them later as additional mathematical input. Therefore, by watching the gestures that children produce as a type of mathematical output, it is possible to map out what math concepts they may already have some knowledge of implicitly. Taken together, these studies' findings are consistent with the proposed model; that the gestures which children produce as a form of math output are linked to the knowledge stored within their long-term memory.

These markers of conceptual knowledge are found for other domains of math knowledge too. Specifically, Gunderson et al. (2015) studied 3–5-year-old children's mismatches in the context of cardinality, an early math concept that involves an extended learning process. Children who were still in the process of learning about this concept were more than twice as accurate in their gesture responses compared to their speech. Moreover, the gestures children produced were more accurate when the information in their gestures was a mismatch with their speech. Therefore, even young children who are in the process of learning a basic numerical concept provide unique information in their gestures that are not otherwise found in their speech. This finding supports that the current model may be extended to consider mathematics more broadly, as the patterns and information in gestural mismatches appear in the form of gestural math output with younger children as well.

There is also evidence of this phenomenon in manual languages, such as American Sign Language (ASL). Goldin-Meadow et al. (2012) examined how the gestures produced by ASL-signing deaf children (*n* = 40) in the previously explained mathematical equivalence paradigm predicted whether they would benefit from explicit instruction on those problems. In general, the children who produced more gesture-sign mismatches were more likely to succeed after instruction than those who did not. This adds to the evidence by suggesting that mismatches occur even within the same modality and strengthens the claim that it is critical to observe children's gestures as a form of math output regardless of the modality of their language. Additionally, this finding highlights how the proposed integrated model may be extended for populations who use manual languages as well, though future research is required to further support each proposed connection.

In addition to studying whether the knowledge children express in gesture can be made available to them, it is also important to understand whether an external observer can recognize the utility of children's gestures. In other words, how does the literature support the connection within the model between children's self-produced gestures and the math input they receive? One such study investigated this connection by recruiting a set of teachers (*n* = 8) to work with 3rd and 4th graders (*n* =38) on mathematical equivalence problems (Goldin-Meadow & Singer, 2003). Specifically, each child completed a pre-test of six problems and explained their solutions to an experimenter. The teacher watched this pretest to gain insight into the child's knowledge but was given no information or instruction regarding gestures. Each teacher then provided instruction on a set of problems before the child completed another, comparable posttest. Results showed that teachers were more likely to have variation in their instructions (e.g., give additional strategies) to children who had used more gesture-speech mismatches during their initial explanations. Therefore, children's gestures (math output) inadvertently shaped their learning environment by evoking further explanation and support from the teacher (math input). Not only does this happen spontaneously, but research shows that when adults are instructed to watch children's gestures, it can amplify the amount of information they were able to glean from children's gestures (Kelly et al., 2002). Even when the instruction was subtle, included different domains of knowledge, or different aged children, these results held. Thus, it is possible to pick up on the information children possess implicitly by watching their gestures and responding to these gestures in ways that may specifically scaffold the children's knowledge. These findings strengthen the connection within the integrated model between children's own math-output informing new math-input.

In sum, prior research provides evidence that self-produced gestures may benefit children's learning and problem solving. These studies support the proposed, integrated model in several specific ways. First, they emphasize the modeled connection between math input in children's environment and the subsequent impacts the input has on their math performance and learning. Second, literature that uniquely considers spontaneous or instructed self-produced gestures allows for additional insight to be added to the model, such as how individual differences in children's knowledge led to differences in children's use of gestures, or differences in the benefits of gesture use itself. The same results are not reported with similar methods which employ physical action, which suggests that these mechanisms are unique to gesture. Additionally, prior research underscores the importance of centralizing the child within the model, given that a learner's math knowledge and cognitive abilities can change the utility of gesture. Lastly, there is evidence suggesting that children's gestures are an indicator of their knowledge and that this form of math output can be used as a tool by adults. This crucial collection of studies provides the connection within the GME model between children's gestures as math-output impacting the mathematical input they receive from others. Taken together, these studies highlight the necessity of a model where children's self-produced gestures in math environments can be studied further.

Math and Executive Function

Numerous studies have demonstrated a relation between children's mathematics ability and their executive function (for reviews, see Bull & Espy, 2006; Bull & Lee, 2014; Cragg & Gilmore, 2014; Jacob & Parkinson, 2015; Peng et al., 2016). Broadly, this relation is consistent across different mathematical areas, including early numerical tasks, arithmetic problems, word problems, and standardized math measures (e.g., Lee et al., 2009, Bull et al., 2011; Van der Ven et al., 2012). It is critical to note that in both empirical and applied settings, executive function has been conceptualized in numerous ways with researchers using a variety of assessment measures. As a result, empirical work on relations between math and executive function is extensive and this literature has been previously reviewed as noted. Therefore, the focus of this section is to briefly summarize this research to demonstrate how the representation of executive function within the proposed model provides a specific operational system that is firmly connected to math contexts throughout childhood.

Cross-sectional correlational research has shown that different sub-components of executive function are related to children's mathematical performance. For example, research indicates that working memory abilities are related to a range of mathematical tasks, such as early numeracy abilities (Kroesbergen et al., 2009), arithmetic achievement (Navarro et al., 2011), problem solving more broadly (Swanson, 2004), written and verbal calculation

(Andersson, 2008), as well as mathematical word problem accuracy (Andersson, 2007; Zheng et al., 2011). Similar findings have shown connections between children's inhibitory control abilities and their math performance and achievement (Brock et al., 2009; Espy et al., 2004; Gilmore et al., 2013). There is additional evidence that inhibitory control, attention shifting, and working memory independently account for separate variance in children's math ability (Bull & Scerif, 2001). Further, when different sub-components of executive function were examined in parallel, the unique contributions of each on children's math ability were still prevalent (e.g., Bull & Scerif, 2001; Kroesbergen et al., 2009; St Clair-Thompson & Gathercole, 2006). Thus, evidence demonstrates relations between all three sub-components of executive function and mathematics in children, lending support to including these factors within our model.

As children's mathematical knowledge develops, the impact of executive function ability on their learning and performance differs. For children, it appears that working memory is of particular importance. Specifically, both children's symbolic (Caviola et al., 2012) and non-symbolic math abilities (Xenidou-Dervou et al., 2013) are positively related to their working memory. Importantly, children appear to rely more on their working memory than adults while solving math problems (Cragg et al., 2017). This may be due in part to how children's enactment of strategies is a more active and less efficient process and so their ability to enact a problem-solving strategy may be more of a direct result of their executive function abilities compared to adults. Further, different executive function abilities may allow an individual to enact different mathematical strategies (Imbo & Vandierendonck, 2007). For example, first-grade children with higher working memory abilities were found to use more correct and sophisticated strategies on arithmetic problems compared to children with lower working memory capacity (Geary et al., 2012). These findings suggest that the relevance, contribution, and demand of working memory and broader executive function abilities may shift depending on both the mathematical content and children's task knowledge, which can impact overall task performance. Thus, individual variation in executive function abilities is a critical component to include in a model of children's math performance and learning, which is reflected in the centralized location of the proposed model.

Lastly, longitudinal studies have shown that children's executive function is not only predictive of later mathematics performance (Alloway & Alloway, 2010; Monette et al., 2011) but also of their growth in mathematical abilities (Clark et al., 2013; Geary, 2011; LeFevre et al., 2013). For example, in a study following children from kindergarten to third grade, working memory related to children's early and later number competencies, which contributed to their math achievement (Krajewski & Schneider, 2009). However, training studies have shown mixed results. Some studies have found that executive function training can improve children's numerical knowledge (Holmes et al., 2009; Holmes & Gathercole, 2014; Ramani et al., 2017, 2019; St Clair-Thompson et al., 2010). For example, training working memory improved kindergarten children's counting skills and performance on working memory games that included both numerical and non-numerical information improved children's counting and numerical comparison skills (Kroesbergen et al., 2014). However, others have found that providing children with executive function training does not necessarily improve their mathematical knowledge (Jaeggi et al., 2012; Shipstead et al., 2012; Karbach et al., 2015). These findings suggest varying levels of efficacy in executive function training on improvements in mathematics and provide the first window of opportunity for future research using the proposed model.

Overall, there is consistent cross-sectional and longitudinal evidence of relations between executive function and mathematical achievement in children. These connections are found in a variety of mathematics domains, and the individual differences in executive function abilities can influence children's mathematical performance. However, experimental evidence demonstrating that training executive function can improve children's mathematical knowledge is less consistent, although numerous studies have shown promising results.

Gesture and Executive Function

Given the multi-faceted role of gesture in children's math environments, it is critical to examine how the current literature supports the model's proposed connections between gestures and children's EF. Research outside the domain of mathematics has linked gesture specifically to executive function from an early age (e.g., gesture, language, and EF; Kuhn et al., 2014). As previously discussed, an individual's gestures may show information about implicit knowledge that is not found in their speech (Broaders et al., 2007; Pine et al., 2007). By shifting this information outside the mind and onto the hands, gesture is commonly proposed as a mechanism by which the user can "lighten their cognitive load" (Goldin-Meadow et al., 2001; Wagner et al., 2004). The idea of cognitive load is often presented as an offloading of related memory resources. While previous work has not drawn explicit connections to components of executive function, more recent work has begun to begin to delineate how gestures may be related to each subcomponent of executive function. Thus, in this section, the literature regarding gestures is reviewed, as well as their implied or direct connections made to the subcomponents of executive function presented within the integrated model.

Working Memory

Working memory is a limited capacity sub-system of executive function where information is temporarily held and processed during problem solving. On average, children use more gestures when faced with an explicit working memory demand (Delgado et al., 2011). The mechanistic connections between working memory and gesture are commonly discussed within the math and gesture literature. For example, the aforementioned study by Goldin-Meadow et al. (2001) examined how children's memory could be impacted if they used gestures during some parts of the common math-equivalence task, then told to keep their hands still during other parts. Results indicated that participants performed better on the memory task when they were able to use gestures. This suggests the use of gestures allowed for a reduction of working memory load, compared to when participants had to speak without gesturing. The authors suggest the use of gestures allowed for a reduction in working memory demands, allowing for a greater allocation of cognitive resources for the memory task, thereby improving performance. This same finding was found with adults. Using an updated, age-appropriate set of math problems to solve and explain as well as a harder set of memory items, adults were told they were allowed to use gestures only on some of their explanations. Similar to children, adults' performance was better when they were able to use gestures compared to when they only used speech, suggesting that both children and adults who use gestures while they speak would benefit from a reduction of working memory demands (Goldin-Meadow et al., 2001; Wagner et al., 2004). Thus, the current model reflects the direct connection between children's gestures and their working memory.

Ping and Goldin-Meadow (2010) further explored the mechanisms underlying how gestures benefit working memory. In this study, 2nd and 3rd-grade children (M age = 8.75 years) watched as an experimenter perform Piagetian conservation transformations. Children were asked to remember a list of words, then turned around to explain conservation to a new experimenter at another table. The new table was either empty or had the same conservation objects. This manipulation was critical as it allowed the researchers to test whether the cognitive benefits of gesture were based on its bodily capacity to link to a specific object or location (e.g., Ballard et al., 1997; Glenberg & Robertson, 1999). However, children who used gestures during their conservation explanations performed better on the memory task even when the items were absent and could not be directly indexed by a gesture. Therefore, the working memory benefits of gesture are not tied to any specific object or spatial relation within the external environment.

More recent research with adults emphasizes the specific connection between gesture and working memory. For example, adults who are asked to use gestures may experience differential working memory benefits depending on their initial working memory abilities (Marstaller & Burianová, 2013). Additional studies have shown that people who have either lower visuospatial or verbal working memory capacity tend to produce more gestures on average (Chu et al., 2014; Gillespie et al., 2014; Pouw et al., 2016), and those who have higher than average visuospatial working memory abilities seem to be better equipped to detect information conveyed in gesture (Wu & Coulson, 2014a,b; Özer & Göksun, 2020). Thus, the connection between gesture and working memory is well-established.

The results of these studies are represented in the proposed model. Specifically, the proposed model reflects the bidirectional flow of information processing between children's gestures and their working memory. This highlights the critical question of whether individual working memory abilities change how children receive gesture-based math input, as well as whether an individual's propensity to gesture could be impacted by their working memory abilities. In other words, would a child's initial working memory ability explain variability in their subsequent use of gestures within a math task?

Currently, there is not enough work available to answer this question. However, one recent study sought to address the related issue of whether the flow of information processing should vary based on a child's initial domain-general cognitive abilities. Specifically, recent research with preschoolers (*n* = 81) found that their spontaneous gestures and working memory were related to their performance on an age-appropriate math task (Gordon et al., 2021). However, children's gestures were not significantly related to their working memory after controlling for age. This work leaves room for future research to investigate this dynamic relation in further detail.

Attention

Attention, like other components of executive function, has been referenced by numerous titles and subsequent definitions in the cited literature (e.g., attention, attention direction, cognitive/mental flexibility, attention/set/task switching/shifting). A commonly understood interpretation often involves a description of a behavioral skill whereby an individual can shift their concentration from one part of a situation, task, or set to another based on what the circumstances require. This direction can be spontaneous in the event of a particularly distracting set of additional stimuli, or it can be influenced by instruction. Furthermore, in studies relating to gesture this part of executive function is often discussed as a piece of the mind that can be directed both from external and internal sources. In other words, watching someone else gesture can facilitate a shift in attention, as can the use of an individual's gestures. Depending on the context and goal of the task, these gestures can act to boost attention directed towards or away from the relevant task components (e.g., pointing).

The breadth of work relating to this ability, or sub-attentional capacities is broad. For example, the utility of gesture itself is linked to attention-seeking and goal-directed behaviors. Research with infants indicates that they attend to pointing gestures before 6-months of age (Rohlfing et al., 2012). Shortly after 1 year, they begin to make their attention-directing gestures to convey and request information from other people in their environment (Kovács et al., 2014;

Tomasello et al., 2007), suggesting at least a basic understanding of the attentional function of gesture. Therefore, within the proposed model, children could be expected to both use and recognize the utility of gesture as a tool for attention.

However, the primary function of gesture is not only to drive attention. For example, one of the previously described studies exposed children to math gestures that contained task-relevant information, but also directed their attention to irrelevant components of the math problem (Goldin-Meadow et al., 2009). Results showed children who saw these partially correct gestures still learn more than children who received no gestures at all, suggesting that even though their attention may have been drawn to less relevant components, the gestures still helped. Nevertheless, attention has still been added as its separate component within the proposed model, given that children in this study still learned the most when they received a gesture that contained both the task-relevant strategy information and directed their attention to the relevant parts of the problem. Therefore, it is important to include within the model that gestural math input can direct children's attention towards relevant information within their environment.

Recent research lends additional support to retaining attention in some way within the proposed model. Specifically, Wakefield et al. (2018) investigated how gestural input could change children's visual attention during math instruction. Eight- to ten-year-old children (n = 50) participated in the math equivalence paradigm and watched videos of a teacher's instruction in speech alone or speech and gesture. Children's eye movements were captured using eye-tracking technology, and their learning progress, as well as concept transfer, was assessed. Children who received both speech and gesture instruction spent time looking at both the problem and the gestures. Additionally, children who received instructions with both speech and gesture were more likely to follow along visually. Following along was uniquely predictive of learning for those in the speech and gesture condition. Therefore, gesture as math input appears to moderate the impact of visual attention on learning and provides additional support for the inclusion of a connection between gesture input and attention within the proposed model.

The current model also ties children's self-produced gestures to their attention. There are limited empirical examples that directly test how children's gestures drive their attention in ways that impact their math output and learning. However, Alibali and Kita (2010) assessed whether prohibiting children's gestures would result in a shift of focus away from task-relevant information, which provides equal insight into this part of the model. In this study, researchers asked whether prohibiting 50 children (M age = 6 years, 5 months) from gesturing in the standard Piagetian conservation task would cause them to shift focus away from the perceptual-motor information which is commonly expressed in gesture. At first, all children were allowed to explain the conservation task with gestures, and then half the children were prohibited from gesturing for the second round of explanations by wearing a muff on their hands. On average, children were more likely to focus on information that was not perceptually present when they did not have access to gestures. When they were allowed to gesture, their focus shifted to the perceptually present information instead.

It is important to recognize that the proposed model does not include one connection built within the literature; that children’s gestures may drive their attention. Specifically, it has been suggested that individual speakers have a threshold for producing gestures and that it may be possible for speakers to take advantage of this threshold (either directly or implicitly) to reap the cognitive benefits of gesture (Alibali & Nathan, 2012), suggesting a possible benefit between gestures to attention or attention-shifting executive function abilities. The GSA framework provides a theoretical outline of how self-produced gestures are a consequence of a speaker's activation of own motor system involved in both planning and producing speech (Hostetter & Alibali, 2008). However, based on this review of the empirical and theoretical work, there is not enough additional support literature to draw a direct line from children's math gestures to their attention. As such, the GME model only represents a flow of information routed by proxy of children's broader executive function processes. Taken together, the results indicate that children's gestures highlight information within their environment, and this information could be used in further cognitive processing related to children's later output. Therefore, while the main mechanism underlying gesture is not attention, it is still an essential component of EF. As such, the unidirectional connection drawn between gesture and attention within the GME model as it stands is supported.

Inhibitory Control

Inhibitory control can be defined as the cognitive ability which allows individuals to stop initial responses, inhibit irrelevant or unimportant distractors, and select behavioral responses more in line with their task-relevant goals. Given the breadth of research spanning across different domains of research, Macleod’s (2007) cognitive definition of inhibition also applies: “Cognitive inhibition is the stopping or overriding of a mental process, in whole or in part, with or without intention” (p. 5). Thus, there is a vast literature on inhibition and the numerous names and sub-components it can be referenced by (e.g., repression, suppression, restraining, response inhibition, inhibition, cognitive inhibition, inhibitory control, inhibitory processes, conditioned inhibition, distractor suppression, inhibition of return, attentional-inhibition, resistance to interference, prepotent response inhibition, etc.; for more, see Macleod, 2007). Numerous definitions surrounding the general abilities of “inhibition” have been defined, tested, and delineated in some capacity from the others. Here, the goal remains to review and assess the limited literature that provides an already small and occluded window onto the connections between inhibitory control, math, and gesture. Thus, the reviewed literature here includes several definitions related to inhibition, coupled with a temperate accord that this is not meant to misrepresent each field's specific term and definition. Rather the goal is to provide an overarching understanding of how inhibition of young children's executive function can further influence their early math problem solving.

Furthermore, while inhibitory control is an important component of executive function, it is noticeably absent from the proposed model. This is, in part, because less is known about the role of inhibitory control as it pertains to both early mathematics and children's subsequent use of gesture. One study, Hurst et al. (2021) considered how higher-level skills such as proportional reasoning could be bolstered in children ages 5 to 7 by the application of gestures by highlighting relevant information relating to equivalence. While there were no direct effects of training, children who received training with relevant mathematical gestures faced less numerical interference (misleading "countable" information, such as discretized markings on images conveying fraction information) than those who received less relevant or no gestural training. However, implications regarding any associations between inhibitory control and gestures as well as other components of the GME model (e.g., Working memory and children's relevant mathematical knowledge) were not discussed. Additional work by Cragg and Gilmore (2014) illustrated a theoretical model where each part of executive function relates to math knowledge in a constant relation over time, the connections between inhibitory control and math knowledge are said to change over time (specifically, procedural, and factual knowledge). In other words, inhibitory control is particularly important for young children who rely on the ability to suppress less sophisticated strategies such as counting from the larger addend in arithmetic (e.g., procedural knowledge), as well as the ability to suppress an incorrect answer that is based on a related incorrect math fact (e.g., math factual knowledge).

Inhibitory Control, Math Problem Solving, and Learning. Compared to other components of executive function, studies of the relations between children's inhibitory control and mathematics reveal nuanced trends. Overall, the general trends do suggest that inhibitory control predicts performance in mathematics (Gilmore et al., 2013; Kroesbergen et al., 2009; Lee et al., 2012; Thorell, 2007) such that performance on inhibition tasks relates to their grades in mathematics (Brock et al., 2009; Visu-Petra et al., 2011) and on standardized math tests (Nayfield et al., 2013; St Clair-Thompson & Gathercole 2006). These trends are also prevalent for young children across various levels of family-level socioeconomic status (e.g., Fuhs & McNeil, 2013). Furthermore, children's inhibition abilities have been implicated as a mechanism for arithmetic problem solving, such that inhibitory control ability predicts future success on measures of arithmetic above and beyond the effects of age, verbal abilities, and maternal education (Blair & Razza, 2007; Espy et al., 2004; Clark et al., 2010). These findings suggest that the role of inhibitory control in arithmetic may be noted in a child's behavior during arithmetic problem solving where they may or may not be able to stop the use of a commonly used strategy in place of the implementation of a more effective strategy based on new conceptual math knowledge. For example, children's inhibitory control has been linked to differences in both procedural and factual arithmetic knowledge (Robinson & Dubé, 2013) and their overt arithmetic problem-solving strategies (Siegler & Araya, 2005).

However, growth in inhibitory control ability over time, the specific domain of math that is being studied, as well as the age range of the subjects and subsequent skill level that could thus be expected, each impacts the interpretability of results. As Cragg and Gilmore point out in their 2014 review, the other components of executive function such as working memory appear to relate to facets of mathematical knowledge (e.g., facts, procedures, and concepts) stably over time. However, empirical work suggests that the role of inhibition shifts and the relation between inhibition and mathematical fact and procedural knowledge can be tenuous with age.

Furthermore, the specific method used to assess children's inhibition abilities may dynamically change how "inhibition" is measured and its subsequent relations to early math, which further compounds the above issue. These methods range from directly testing inhibition, or another sub-component using a parent or teacher rating (e.g., the Behavior Rating Inventory of Executive Function; Gioia, Espy, & Isquith, 2003; see Clark et al., 2010 to relate the score on mathematics assessments), or even by extrapolating results from tangentially related tasks. There is a long list of tasks used to assess children's inhibitory control that have contributed to the "task impurity problem" (Miyake et al., 2000). In essence, it is difficult to assess inhibitory control using just one task, as these methods often tap into other components of executive function as well as language and motor skills and may also be prone to measurement error.

Even so, unique approaches to how inhibitory control could be conceptualized continue. For example, in a study relating children's working memory, inhibitory control, and arithmetic problem solving to one another, there were no direct measures of inhibitory control. Instead, the authors approached inhibition through the working memory measures and assessed how often children made intrusion errors on the tasks, which are answers that contained information that should have been inhibited (Passolunghi & Siegel, 2001). This approach follows that children who struggle with mathematics problem solving may score lower on a working memory task due to a two-fold problem. First, they may have lower working-memory capacity. Second, the efficacy of their inhibition may make it harder for them to access the target information needed in their long-term memory, thus resulting in an "intrusion" error where they answer with information that is still in the short-term memory system. Therefore, this indirect measure of inhibitory control allowed researchers to draw the connection showing that poor problem solvers of arithmetic also tend to have a higher number of intrusion errors during recall tasks. In other words, difficulties in arithmetic problem solving can be related to a lower working memory span, as well as the necessary attentional and mental resource capacities required to inhibit irrelevant information.

Other common methods used for assessing inhibitory control ability are often described as measuring response inhibition or interference control (For a review see Nigg, 2000), which are both described as facets of inhibition. Studies concerned with response inhibition focus on an individual's ability to suppress an action given a particular context or set of rules that could interfere with specific goal-driven behavior. Conversely, interference control is a broader referent, understood as an ability to ignore distracting stimuli. Importantly, these abilities are not argued to be mutually exclusive, and the specific terms are sometimes used interchangeably. Thus, by separating the literature into additional constructs, additional constraints are added regarding how the findings from each study may be understood with other studies of inhibition.

Response inhibition is typically assessed using Go/No-Go or Stop-signal tasks which frequently make one response until they are shown a different stimulus indicating they should suppress that response. In these tasks, inhibitory control ability is higher based on how well a person can withhold the prepotent response and has been used to compare children's inhibitory control to mathematics abilities (Friso-van den Bos & van de Weijer-Bergsma, 2020; Monette et al., 2011; St Clair-Thompson & Gathercole, 2006). On the other hand, the Stroop task is the most well-known measure of interference control; participants are presented with stimuli (the word "red") and are asked to respond to one aspect of the stimulus (e.g., the color of the text, here printed in black) in the presence of distracting information (e.g., automatically reading the word "red"). This calls for the ability to suppress the distracting information and if this suppression fails, it leads to an incorrect response. Variations of the Stroop task have been frequently used to assess how inhibition relates to children's mathematics performance broadly (e.g., Bull & Scerif, 2001, Monette et al., 2011, Gómez et al., 2015), including relating to their arithmetic performance specifically (e.g., low inhibitory processes relate to low scores on early arithmetic performance, Navarro et al., 2011). Variations of this task have even been used to continue to assess these relations with adults, who complete assessments in math ranging from basic arithmetic up to integral calculus, showing that inhibition was a predictor of calculation performance (Coulanges et al., 2021). For young children, Purpura and colleagues (2017) administered a battery of mathematics, literacy, executive function (including Stroop for response inhibition), and general cognitive ability to preschool children between 3 to 6 years old. Results indicated that children's early mathematical scores were related to response inhibition, including some measures of arithmetic (e.g., story problems; ''Johnny had one cookie and his mother gave him one more cookie, how many cookies does he have now?"). However, initial correlations between inhibition and some measures of early mathematical skills were tenuous with age, including a formal addition task (e.g., Showing "1 + 1 = …" while asking ''How much is…"). In other words, the formal task required children to have specific levels of print-related content knowledge to succeed.

Another common assessment of inhibition is the Eriksen Flanker task (Eriksen & Eriksen, 1974; NIH Toolbox: Cognition Battery, see also Zelazo et al., 2013). In this task, participants are faced with navigating specific rules regarding responses to stimuli (e.g., press the arrow key that matches which direction the middle arrow is facing) which require a controlled response to a set of conflicting or competing stimuli (the middle arrow points left, all other arrows point right), as well as the possibility of inhibiting a motor output (e.g., clicking a key on the left rather than the right). The Flanker task has been used to determine the relations between children's inhibitory control and mathematics abilities in neurocognitive studies (Wilkey & Price, 2019). The Flanker task was only one of several in a battery of tasks children were administered in the formation and standardization of the NIH Toolbox executive function assessment. As children across a wide age range were able to complete the assessment with adequate levels of reliability, validity, and sensitivity, this allowed researchers to detail several developmental trends beginning early childhood through to adolescence. For example, correlations between the NIH Toolbox executive function measures were higher for younger children (3 to 6-year-old children) than for older children (8 to 15-year-olds) suggesting that improvements in executive function were emerging through a slow refinement and eventual division of executive function into more refined sub-skills (Zelazo et al., 2013). Researchers have used the Flanker task with preschool children to show that inhibitory control makes a unique contribution to children's early arithmetic abilities after accounting for working memory, age, and receptive vocabulary (Harvey & Miller, 2017). Thus, while behavioral research varies in its definitions and measurements of inhibitory control, there is a consensus that inhibition is related to children's early mathematics ability. Moreover, it appears to be a unique predictor of arithmetic ability, even after accounting for related factors such as age, other components of executive function, literacy, and demographic variables.

Inhibitory Control and Gestures. Empirical research assessing the connections between children's gestures and their inhibitory control abilities during mathematical contexts is sparse. However, studies from other domains provide some insight into these connections. For example, research in the domain of analogical reasoning, where individuals must rely on featural and relational knowledge in their long-term memory to understand and complete a task, suggests that children's inhibitory control may act as a gating mechanism for their working memory abilities (Morrison et al., 2011). In other words, during problem solving, inhibitory control is responsible for what information remains active in working memory, whereby higher inhibitory control leads to better and/or more efficient maintenance of the storage of information in working memory, in turn resulting in more relevant and goal-directed answers in the analogical reasoning task. An experimental study sought to investigate whether these results persisted in young children (4 to 5-year-olds) and investigate the possibility that providing instruction that was paired with gesture would draw focus to task-relevant information and away from the featural distractor during problem solving (Guarino et al., 2021). Children who saw instructions with gestures allocated their visual attention away from the featural distractor and were better able to follow along with the spoken instruction. While these results were not predictive of posttest performance, the authors note that gesture was supportive of the visual attention during the instructional session. In other words, when gesture is used, visual attention patterns mirror those more mature patterns which would be expected from an individual with higher inhibitory control (e.g., not at the distractor stimuli). Furthermore, the authors note that if inhibitory control does act as a gating mechanism to working memory, this mechanistic function may not yet be in place for younger or less knowledgeable individuals. For example, studies related to gesture instruction show that gesture tends to be more advantageous for children who have reached a pre-existing level of relevant knowledge related to the concept being taught (for an example of mathematics see

Congdon et al., 2018; for an example of language see Wakefield & James, 2015). Taken together these studies indicate that individual inhibitory control abilities may act as a conduit, such that task-relevant information is directed (or redirected) to working memory, while others are inhibited, based on goal-relevant information. Thus, inhibitory control interacts with the flow of information during processing and problem solving.

In addition to the literature supporting the role of gesture from an observational standpoint, research has also shown the utility of using gesture to boost performance during tasks that require inhibitory control skills. For example, O'Neill and Miller (2013) investigated the role of preschoolers' gestures (M age = 47 months) during a Dimensional Change Card Sort task. Children (*n* = 41) were asked first to sort cards based on a given rule (e.g., sort cards by color), then midway switched to sorting the cards by a new rule (e.g., sort by shape). To sort successfully, children must inhibit the first rule to sort by the new rule. Overall, children who gestured more had higher performance. Further still, children who used specific task-relevant gestures during the card sort task, such as pointing out specific indicators of the rules on the cards themselves, had higher performance compared to children who used less relevant gestures. Most differences in performance were noted after children were supposed to adhere to the rule shift, such that the utility of gesture appeared at a crucial junction, given that the rule switch requires them to inhibit the old rule to implement the new one. Furthermore, work with preschoolers using the same card sort task assessed whether a direct, causal relation existed between preschoolers' gestures and their scores on another version of the Dimensional Change Card Sort task (Rhoads et al., 2018). Specifically, preschoolers received training to use gestures as a support during the task to retain the specific dimensions they were using to sort. On average, children who were instructed to gesture showed improved sorting accuracy, and these instructions appeared to be particularly beneficial for younger children. These results suggest that instructing children to use gestures may boost their overall executive function performance, or even lead to specific improvements in their inhibitory control abilities.

A new version of the GME model: Accounting for the gate-keeping mechanism of inhibitory control. The current chapter focuses on the function of gesture across learning contexts broadly (e.g., Goldin-Meadow & Wagner, 2005) and reviews how the GME model outlines the role of gesture in math environments. The processes involved in math learning are well-modeled by the Information Processing Approach, however, this approach is not able to fully explain the underlying mechanisms of gesture. Thus, the GME model includes tenets of Wilson's (2002) presentation of embodied cognition by drawing connections between the mind, the body, and the surrounding environment. This allows for a consideration of gestures as a form of math input from the environment, as well as a form of math output from children's bodies. The review of the relevant literature for each of the GME model components highlights the connections between math, gestures, and executive function, as well as how gestures can influence these abilities both as a form of both math-input and math-output.

Critically, this review outlines how inhibitory control is drastically understudied compared to the other parts of executive function and their connections to gesture use in early mathematics environments. Math contexts are particularly useful to study how children employ their inhibition abilities. During problem solving, children can inhibit old, ineffective, or incorrect strategies in place of new or correct strategies they have learned more recently (Siegler, 1996). This highlights the need for examining the role of how children’s gestures may relate to inhibitory control during problem solving. In particular, the current study seeks to address the gaps in the current literature by adding inhibitory control to the GME model (see Figure 2 for the proposed changes to the GME model to include inhibitory control).

Prior work emphasizes gestures' primary theorized mechanistic function as a cognitive tool whereby users receive a subsequent decrease of working memory load, and in turn impacting inhibitory control (e.g., Gesture Feedback Model; Morsella & Krauss, 2004). This is relevant to how gestures may scaffold children's abilities in mathematics learning and problem solving. For example, high-gesturing children could be expected to attempt to keep new information related to new mathematical facts and procedures in mind and inhibit irrelevant strategies they may have used to solve more novice mathematical tasks. Furthermore, providing direct visual representation to relevant numerical information in arithmetic problems specifically (e.g., counting on your fingers to track addends) supports broadly children's cognitive load suggesting that the dynamic gatekeeping facilities of inhibitory control and burden on working memory could both benefit.

Based on previous literature in domains related to but outside of mathematics, children's gestures likely help to keep new rules in mind, inhibit an old rule, or some combination of the two. While the GME model provides a breakdown of executive function and the information that flows between the sub-systems of attention shifting and working memory, further research needs to be conducted to better understand how to incorporate the third component of executive function, inhibitory control, into the model. Much like math, children's inhibitory control can be shaped by both watching and using gestures. Furthermore, these relations may be further shaped by a child's working memory ability and the level of task-relevant knowledge they already possess. Lastly, the nature of these relations may shift throughout development, and thus should be considered from that perspective.

A new version of the GME model that includes inhibitory control would be required to represent how individual inhibitory control ability can influence an individual's ability to prevent prior knowledge, some of which could be related to previously acquired intuitive understanding, from interfering with the task at hand (see Mareschal, 2016). Furthermore, prior work has shown that solving counterintuitive mathematics problems requires inhibition of incorrect strategies, as well as the possibility of dominant responses (Borst et al., 2013; Linzarini et al., 2015; Lubin et al., 2013), such that both children and adolescents with higher levels of inhibitory control have better performance on counterintuitive mathematics and science problems (Baker et al., 2011; Brookman-Byrne et al., 2018; Vosniadou et al., 2018; Zaitchik et al., 2014). Thus, a new version of the GME model, which includes inhibitory control, would need to include a modulating connection, whereby children's individual inhibitory control ability leads to a split in the flow of information during problem solving. Specifically, children with low inhibitory control could be prone to relying on information that was most previously learned, or intuitive. Thus, representing this information flow would likely follow a pathway to the child providing a verbal solution based on a failure to inhibit a prepotent response (e.g., sensory register → attention → working memory → inhibitory control fails to loop back to working memory processes for further consideration → child's verbal response). However, in the instance that the child has higher inhibitory control, leading to successful inhibition, inhibitory control allows for a feedback loop to the information stored within the memory and could enact strategies using that information (e.g., gesture or mental based strategies).

Summary

The current chapter focuses on the function of gesture across learning contexts broadly (e.g., Goldin-Meadow & Wagner, 2005) and reviews how the GME model outlines the role of gesture in math environments. The processes involved in math learning are well-modeled by the

Information Processing Approach, however, this approach is not able to fully explain the underlying mechanisms of gesture. Thus, the GME model includes tenets of Wilson's (2002) presentation of embodied cognition by drawing connections between the mind, the body, and the surrounding environment. This allows for a consideration of gestures as a form of math input from the environment, as well as a form of math output from children's bodies. The review of the relevant literature for each of the GME model components highlights the connections between math, gestures, and executive function, as well as how gestures can influence these abilities both as a form of both math-input and math-output.

Critically, this review outlines how inhibitory control is drastically understudied compared to the other parts of executive function and their connections to gesture use in early mathematics environments. Math contexts are therefore especially useful for studies which hope to investigate differences in children’s inhibition abilities. During problem solving, children can inhibit old, ineffective, or incorrect strategies in lieu of new or correct strategies they have learned more recently (Siegler, 1996). This highlights the need for examining the role of how children’s gestures may relate to inhibitory control during problem solving. In particular, the current study seeks to address the gaps in the current literature by adding inhibitory control to the GME model (see Figure 2 for the proposed changes to the GME model to include inhibitory control). Children’s inhibitory control will be tested in relation to the primary outcome of interest, gesture use in an arithmetic task, while also including additional predictors and correlates of both gesture and math to account for how unique variance in children’s inhibitory control ability may result in differences in the outcome.

Chapter 3: Method

Participants

Participants were 137 children, ages between 4 – 7 years at their first session (M_{age} = 5.75 years; range = 4.10 years – 7.80 years; 50% female) and their parent/caregiver. All children were English-speaking, and from the United States (approximately equally distributed by gender and age group, see Table 1 for full subject breakdown). This age range was selected due to prior studies indicating the rapid co-development of early math knowledge, inhibitory control, and working memory.

Initially, 142 families were recruited. However, participants were excluded in the event they did not complete sessions 1 and or 2 (*n* =4), and an additional child was recruited but excluded from the study because the Zoom video failed to record for session 2 (*n* = 1). The remaining sample size of 137 study participants exceeds the recommended ratio of sample size to number of free parameters (5 to 1; Bentler & Chou, 1987). Importantly to the current study, statisticians advise samples with less than 200 subjects may still be effective when testing models with latent variables that have strongly correlated constructs (Kenny, 2015).

Participants were recruited from social media posts (e.g., Facebook, Twitter), and online data collection websites (e.g., ChildrenHelpingScience.com), as well as information shared on the study website (www.umdterrapingamesstudy.com). Participation was limited to the United States, based in part on the generalizability of normed measures (e.g., BRIEF/BRIEF 2 normed on US data alone) as well as restrictions to payment of participants (USD via Amazon gift cards). Figure 3 provides a map of participants' geographic locations. After study completion, parents were asked to complete an optional demographic survey (items listed in Appendix A). Table 2 shows descriptive statistics for these demographic survey variables.

Design

This study utilized a cross-sectional design to investigate how children's inhibitory control, working memory, and early math knowledge relate to children's use of gestures (GME model, Gordon & Ramani, 2021). Children completed two sessions; in session 1 participants completed independent online measures of inhibitory control and early math. Session 2 took place approximately 1.5 weeks later, where children completed measures of inhibitory control, working memory, and an additional early math task where their gestures were video recorded live on Zoom with an experimenter. Parents completed a survey regarding their impressions of their children's inhibitory control and working memory abilities and were asked to fill out an optional demographic questionnaire.

Procedure

Data were collected from children whose parents/guardians agreed to their participation and children provided verbal assent to participate prior to every session. Data collection for the study took place between February 2022 - October 2022 and consisted of one parent survey measuring children's working memory and inhibitory control, a 20-minute asynchronous session where children played inhibitory control and math games online (Gorilla, Session 1), and a 20-minute synchronous session where children meet with an experimenter over Zoom to complete two working memory tasks, one inhibitory control task, and one task to assess math and gesture use (Session 2; for an overview of study measures and timeline see Figure 4). Each construct (i.e., Math, Inhibitory Control, Working Memory) was assessed using multiple measures and combining different methods (e.g., parent survey vs. independent games vs. live session) to account for potential measurement error and to increase the precision within our statistical estimates. All task scripts are included in the appendix.

Parents signed up for the study using the UMD Qualtrics platform where they completed a digital consent form. Upon completion of the Qualtrics survey parents received an email confirmation containing: 1) a link to their BRIEF survey on Pariconnect.com (see Measures: Part 1 for more information) and 2) a link for their child to play the session 1 games in Gorilla (see Measures: Part 2 for more information). After their child completed session 1, families were automatically redirected to the online scheduling platform (Calendly.com), which displayed all team members' availability for session 2. Parents were able to choose a time and date for the visit that was most convenient for them and were subsequently sent a link to their electronic meeting via Zoom[1] with a trained research assistant at their chosen time (see Measures: Part 3 for more information). Parents were then asked to complete the survey on Pariconnect within 30 days of receiving the link. They also had the opportunity to sign up for additional email & text reminders for these appointments.

There were seven experimenters; the author and six undergraduate students. Each of these experimenters were trained by the author and CITI-approved. The author (female Caucasian graduate student) led 21 session 2 visits, approximately 15% of the final sample. All recorded data completed by the experimenters were appropriately de-identified using electronic submission on a computer.

Measures

For a summary of all tasks with subsequent dependent variables, score ranges, as well as details regarding session and hypothesized factor, see Table 3.

[1] Zoom was chosen over other video conferencing softwares based on several notable advantages, as well as its prevalence in online developmental research studies (See Kominsky et al., 2021 for a review). First, it does not require participants to download or set up anything in advance. Second, it allowed our research assistants to screen-share which is vital to our protocol. Lastly, this platform allowed each meeting to have its own unique meeting identifier and password, as well as record directly to the university's cloud storage which is vital to maintain security and participant confidentiality.

Parent Ratings of Children's Working Memory and Inhibitory Control

Digital Behavior Rating Inventory of Executive Function®–Preschool Version. Parents of children ages 4.0 to 5.99 were sent the online version BRIEF®-P, a standardized version of the BRIEF®, specifically made for parent ratings of their preschool-aged children (2 years to 5 years 11 months; see BRIEF®2 for the measure for children ages 6.0 to 7.99 years old). This measure consisted of 63 items and provided parent level ratings of children's working memory and inhibitory control. Each item asked the parent to rate how often their child has experienced the behavior in the past six months, on a scale of Never (1), Sometimes (2), or Often (3). Specifically, this task was normed using data based on "child ratings from 460 parents and 302 teachers from urban, suburban, and rural areas, reflecting 1999 U.S. Census estimates for race/ethnicity, gender, socioeconomic status, and age". For parent samples, it has high internal consistency reliability (.80-.95 for the parent sample) and moderate test-retest reliability (.78-.90). Parents were able to complete and submit the survey using any internet-connected device at any time that was convenient for them. Higher scores indicated poorer inhibitory control and working memory. Therefore, the dependent measures for this task were the inverse of the individual parent report for the BRIEF®P2 inhibitory control and working memory subscale raw scores, respectively.

Digital Parent Behavior Rating Inventory of Executive Function®, Second Edition. Parents of children ages 6.0 to 7.99 were directed to the online version of BRIEF®2, a standardized, 63 item rating scale that provided parental assessment of children ages 5 to 18's executive function abilities, broken into 9 specific subscale measures (including inhibitory control and WM). Each item asked the parent to rate how often their child has experienced the behavior in the past six months, on the same scale from the BRIEF®-P (e.g., Never (1), Sometimes (2), or Often (3)). This measurement underwent rigorous testing to ensure validity and reliability, based on a stratified standardization sample of 3,600 cases matched by age, gender, ethnicity, and parent education level to the U.S. Census. Reliability coefficients for Parent Form were > .90, outcomes are correlated with other measures of behavior (e.g., CBCL & WISC-IV), and it has been used in 800+ peer-reviewed studies worldwide. Parents of children 6-7.0 years were also able to complete and submit this form on their device at any convenient time. Higher scores indicated poorer inhibitory control and working memory. Thus, the dependent measures for children ages 6.0 to 7.99 was the inverse of the individual parent report for the BRIEF®2 inhibitory control and working memory subscale raw scores, respectively.

Session 1: Child Measures of Math and Inhibitory Control on Gorilla

All session 1 measures were administered using the Gorilla.sc platform. Families were told that they can complete these tasks at any time over two days. Once the family was ready to participate, parents would help their child get ready. At the start of session 1, parents logged their child into the Gorilla platform and assisted with the initial setup using voice-over and photo instructions as well as completed checks to ensure their speakers and keyboard were working. All games in Gorilla used child-friendly images and audio which allowed children who are not yet able to read to be able to participate in the study by following along with the images and listening to the audio. Children began with a short introduction task where audio and video stimuli help them to learn and practice pressing the “a” and “l” keys to respond to “left” and “right” sides of the screen, respectively (see Figure 5). These were the only two keys needed for all tasks within the study. After hearing the general instructions, children worked through session 1(Child Flanker, Magnitude Comparison, and Forced Choice Arithmetic tasks). These tasks were grouped given they all require the same left/right keyboard response training protocol.

If children did not complete part or all the tasks in Gorilla for any reason on Day 1 (e.g., leaving the protocol early), parents were contacted and asked to have their children log back in and complete this assessment before their Zoom session. If there were any notable errors in children's data for either the Magnitude Comparison or Forced Choice Arithmetic tasks (e.g., missing trials or long breaks within a task), these tasks were repeated during the Zoom assessment via screen share to ensure results accurately reflected children's best efforts.

Child Flanker Task. Children completed a computerized version of the Child Flanker Task as a measure of inhibitory control (Adapted from Anwyl-Irvine et al., 2020 and Rueda et al., 2004, adapted for Gorilla). Children were first introduced to a fish graphic and the rules of the game. They watched as a row of five fish were presented in a horizontal line on their computer screen (see Figure 6). Participants were then asked to select which direction the middle fish was "swimming" (e.g., which way it was facing, either to the left or right) by pressing the "a" key on the left or the "l". These buttons were selected given that children could more easily keep one hand on each response key and more easily identify the spatial direction (i.e., press the button using the hand that the fish is pointing towards). The task consists of two trial types: congruent and incongruent. During congruent trials, the middle fish was pointing in the same direction as the flanking fish. In the incongruent trials, the middle fish was pointing in the opposite direction as the flanking fish. Participants were asked to answer as quickly and accurately as possible.

After the children watched the task introduction and directions, they participated in 12 practice trials with feedback (e.g., red cross for incorrect responses and a green checkmark for correct answers). The participants then completed four blocks of 24 trials each, with self-paced breaks between blocks, for a total of 96 trials. There are four types of trials that children saw: all fish swimming to the right (25%; congruent), all the fish swimming to the left (25%; congruent), middle fish swimming to the right with flanking fish to the left (25%; incongruent), and middle fish swimming to the left with flanking fish to the right (25%; incongruent). Children made their determination of which way the middle fish was swimming while the fish were still visible on the screen. Between each trial a fixation cross was displayed for 1,700 ms followed by a blank screen that flashed before the next trial was displayed (time of each blank screen varied randomly between 400, 600, 800, and 1,000 ms.).

Based on prior successful research with children in this age group (e.g., Massonnié et al., 2019) there was no timeout for trials within the task and any breaks were self-paced and optional. However, to ensure that reaction times were indicative of actual attempts to respond, all reaction times (RTs) under 200 ms (e.g., an indication that the child responded before their perception of the stimulus) were excluded, as well as any RTs above 3 standard deviations above the mean RT for each subject (to prevent extreme response values from influencing the results). The dependent measure for Flanker tasks was RT cost, which was calculated by subtracting the mean RTs for children's correct answers on the congruent trials from the mean RTs to for their correct answers on incongruent trials. Given that higher values of RT cost are indicative of poorer inhibitory control (e.g., children with lower inhibitory control take longer to provide a correct answer during incongruent trials), the dependent measure was the inverse RT cost for ease of interpretation.

Forced Choice Symbolic Addition (Daubert, 2018; Prather & Alibali, 2011). Children were shown six sets of arithmetic problems on their computer screen and heard narration that these were problems that two imaginary children had already solved (e.g., "Avery says 6 plus 3 equals 9. Jamie says 6 plus 3 equals 10"). Each equation was shown in the form of both symbolic numerals and their corresponding nonsymbolic quantities (i.e., drawings of cookies). They were asked to make judgments about "who solved the problem correctly" by indicating which answer was correct (on the left or the right of the screen) by pressing the "a" for the left or the "l" for the right. Children completed three simple and three complex problems *(*randomly ordered by Gorilla*)*. Children's answers to the questions and reaction time were measured in case of floor or ceiling effects. Given the variability in response, the dependent variable for this measure is the total of items the child answered correctly divided by the total six problems.

Magnitude Comparison (Adapted from Ramani & Siegler, 2008; Ramani et al., 2020). Children were then introduced to a new computer game with images of a wizard and his spell book. The audio narration told them that they can help cast spells by comparing two numbers on the pages of the spell book and selecting which number is larger. Children provided a response of which number is larger by pressing the same key which matches the side of the screen they have been trained on before (e.g., "a" for the left or the "l" for the right). Participants proceeded with one practice trial with feedback and then moved onto 18 test trials with pairs of numerals ranging from 1 to 100 on their computer screen. Children's answers to the questions were assessed and reaction time was measured in case of floor or ceiling effects. Here, the dependent measure is the total number of pairs in which the larger number was correctly chosen out of total trials assessed (18).

Session 2: Zoom Child Measures of Inhibitory Control, Gesture, Math, and Working Memory

Approximately 1 week after the submission of their Gorilla measures (session 1), children were scheduled by their parents to meet virtually with an experimenter online via Zoom for about 20 minutes. This video visit was video recorded in full[2]. The day before the scheduled meeting, parents received a reminder email. On the day and time of the study, the experimenter joined the automatically recording Zoom call, introduced themselves, and set up the participant for the study. Participants were asked to sit in front of their computer screen such that their whole torso, head, and both hands are visible within the video frame (e.g., "Can you sit up nice and tall for me in your chair? Can you scoot back just a bit? Can you tilt your computer screen down just a bit?").

Head Belly (Adapted from Head Feet; Fuhs & McNeil, 2013). Children began session 2 with a modified version of the Head Feet task as a measure of inhibitory control. This task acted as an additional assurance that children are sitting back far enough that the camera captures all hand gestures in the next task. Children were introduced to this task as an "opposites game" and were asked to touch their head when the experimenter said "belly" and their belly when the experimenter said "head". Children were given up to three practice trials for each type (e.g., belly or head) with feedback, followed by 16 test trials without feedback. The experimenter followed a predetermined order of trials and continued forward regardless of whether the child was right or wrong (See Table 4 for order of trials).

Only the first response (defined as the first place they fully touched with their hands) will be counted as the child's answer. False starts were not penalized, such that children who begin to move their hands but do not fully place them on the incorrect area before placing them on the correct area will be given a "correct" score. The dependent variable for this task was the number of correct trials divided by the total (16 trials).

[2] The administration of a similar protocol via Zoom was previously deemed effective with a sample of 98 children ages 5 to 8; Gordon & Ramani, in prep.

Addition Strategy (Barkin & Ramani, Under Review; Adapted from Geary et al., 2004). In this task, experimenters used the screen share function on Zoom to display a PowerPoint, such that children could see the stimuli on the experimenter's computer. The task began with a short introduction where children were told they would see a series of math problems appear on their screen and would need to solve each problem to receive a piece of a "treasure map to find the treasure" (Figure 7). Each time the child solved a problem, regardless of their accuracy, they received a piece of a treasure map on screen (by clicking through slides in the PowerPoint presentation) to help find where the "buried treasure" was hidden. Children were instructed to solve each problem in any way they would like, as quickly as possible without making too many mistakes (adapted from Geary et al., 2004). The assessment began with one example problem (2+2) with feedback to familiarize children with the task administration, followed by 12 single-digit problems presented horizontally on their computer screen, one at a time (see Table 5 for a list of problems). These problems included integers 2 through 10, with no duplicate integers in the same problem (except for the example problem, 2+2). For five of these problems, the smaller number is presented first. One of the problems summed exactly to ten, five summed to a value greater than ten, and the other eight problems were sums smaller than ten. For each problem, the experimenter read the problem aloud (e.g., "What's 2+2") and waited for the child to give a numerical response. This task generated two variables: the dependent variable of arithmetic score, and the outcome variable of children's gesture use.

Arithmetic Score. Children's answers to each addition problem were scored by two independent raters. If the second raters' scores did not match the first (e.g., due to a mistake in score entry on the first rater's part, given that this scoring involves marking what the participant provided as their final answer), the two raters discussed the discrepancy and decided on the appropriate score. The dependent variable for arithmetic score will be calculated as the total correct out of the total problems (12).

Gesture Coding. Reliable, trained raters watched each video and scored the strategy modality used using a previously created coding scheme (ICC *ps* all <.001 suggesting a high level of agreement between raters; Barkin & Ramani, under review). Using a Qualtrics survey, trained research assistants watched each Zoom video recording and categorized children's strategies used for each problem. Prior research emphasizes the consideration of the mathematical type of children's problem-solving strategy (e.g., Siegler & Shrager, 1984; Huttenlocher et al., 1994). However, while these frameworks include more general cognitive skills involved in children's strategy use (e.g., metacognitive system within SCADS Model; Shrager & Siegler, 1998), there is a critical gap of assessing strategy by modality. This gap in the prior literature informs the current study; specifically, the approach here separates strategy use first by modality (e.g., gesture, verbal, mental). This allows for analyses concerned with how these cognitive abilities may relate to gesture strategies specifically. Moreover, this type of coding scheme provides additional details regarding how young children first begin to solve simple addition problems.

Thus, children's strategies were grouped first by modality (e.g. gesture, verbal, combined gesture & verbal, and not overtly observable), then by mathematical content (for a full list of math strategies & definition, see Table 6). For modality coding on each of the 12 test problems, children's specific modality (e.g., verbal, gestural, mental) was scored. This scoring procedure involved marking each time an overt, physical indicator of counting was seen, such as movements of the child's fingers and/or mouth. These instances were further classified based on the specific behaviors used within gesture, gesture with speech, or verbal-alone counting (in the instance no hand movement was observed). Additionally, if no overtly observable behavior was seen (e.g., the child sits and thinks about the problem before answering), then this modality was marked as “unobserved”. The dependent measure for children’s gesture use during a math context classified as the number of problems that a children used a gesture strategy on (either with or without speech accompanying it).

Forward and Backward Span. As a measure of their working memory, children completed forward word span and backwards word span tasks (Adapted from Müller et al., 2012. In Forward Span, children listened as the experimenter read aloud a sequence of one-syllable color words (e.g., red, blue) at approximately a rate of one word per second. They were then asked to repeat those words back to the experimenter in the same order. In the Backward Span task, children listened to a list of animals read at the same rate but were asked to repeat those animals back to the experimenter in reverse order (e.g., “horse, dog” would become “dog, horse”).

In both tasks, the number of words within a trial ranged from two to seven, with two trials at each span level (i.e., two trials of two words, two trials of three words). All children completed two spans of sets sizes two through six, and their responses were recorded during this task. If children did not correctly answer one or both practice trials after additional feedback, the child received a score of 1. Else, they received a score for the highest span they correctly repeated. Thus, the dependent variable for both Forward and Backward span tasks equals the highest span that the child could repeat correctly. Children’s answers were scored live, and then scored after by an independent rater. If the two raters' scores did not match, a third independent rater decided on the appropriate score.

Data Analysis

All data management, cleaning, and analyses were conducted in R (R Core Team, 2020). Beyond the base R packages, the core packages used include tidyverse (Wickham et al., 2019), Hmisc (Harrell Jr et al., 2021), readxl 1.3.1 (Wickham & Bryan, 2019), rstatix 0.6.0 (Kassambara, 2020b), ggplot2 3.3.2 (Wickham, 2016) and ggpubr 0.4.0 (Kassambara, 2020a). All CFA/SEM analyses and visualizations were conducted using laavan (Rosseel, 2012), semPlot (Epskamp et al., 2019) and semTools (Jorgensen et al., 2022).

Missing Data

As described in the methods, children who did not complete their first and/or second session/or whose parents did not complete the BRIEF survey were excluded from the study (n = 5). As such, all included participants had complete cases and there were no instances of missing data for the preliminary and primary analyses (n = 137).

Preliminary Analyses

In order to test these relations within the current study correlations between all measured variables for working memory, inhibitory control, age, and gesture are assessed. Table 7 shows descriptive statistics, as well as the correlations between age and each of the predictors and the outcome (gestures). Each variable underwent scaling (z-scores) to provide a more straightforward interpretation of results and to account for differences in the range of raw scores. Next, an assessment of multivariate normality of the data was conducted using kurtosis > 5, $p < 0.05$ to select an appropriate estimation method. Given the presence of non-normality in the data, maximum likelihood parameter estimates (MLM) were used to fit all models, as they are robust to non-normality (Satorra & Bentler, 2010).

Primary Analyses

Aim 1. Research suggests that during this period of development (e.g., ages 4 to 7.99 years old), children's working memory is rapidly expanding (Gathercole et al., 2004), and their math knowledge is growing. At the same time, younger children in this range tend to rely on gesture-based strategies whereas older children come to use more retrieval-based strategies (Ashcraft, 1982; Siegler, 1996). Research also suggests that the relation between age and gesture use may be attenuated by children's math knowledge (Gordon et al., 2019). To account for the possibility of an interaction effect, linear regressions were conducted where age and math were considered separately as predictors of gesture in addition to an interaction between the two (Table 9). Results indicate that children's math knowledge, and the interactive effect of math by age predicts gestures, but age alone does not. Furthermore, differences in children's gesture use by gender were considered. In the event of differences in children's age or gender, one and/or both variables will be included as covariates in subsequent SEM modeling. Table 10 shows the means, standard deviations for each variable by gender (male vs. female), as well as t-tests to assess any gender differences. Results indicated a retention of age as a covariate for all measures, as well as gender as a covariate for children's use of gesture.

Aim 2. Structural equation modeling was used to examine the concurrent relation between children's inhibitory control, working memory, and math abilities. In all models, standardized (scaled) factors were assessed such that the variance of each factor was fixed to 1, means were set to 0 (z-score), and all loadings were freely estimated. This method is useful as it allows for comparison of items within a solution, versus across groups or time (unstandardized). Measured variables (indicators) are represented in rectangles, while latent factors are represented by circles. Children's use of gesture was the outcome of interest in all models with a fitted regression (Models 4 and 5).

All measurement models were considered using standard fit indices for confirmatory factor analyses (CFA; Hu & Bentler. 1999; Schumacker & Lomax, 1996); chi-square (non-significant values indicate better fit), comparative fit index and Tucker-Lewis index ("Goodness-of-fit" indices; CFI/TLI > 0.95 indicate good fit), root mean square error of approximation (parsimonious index; RMSEA < 0.06 indicate good fit), and Standardized Root Mean Square Residual (absolute index; SRMR < 0.08 indicate good fit). Table 11 shows each models' fit indices. Additional consideration for all item factor loadings was given, such that larger factor loadings indicated better, more discriminating items.

Following the typical practices for structural equation modeling, two different confirmatory factor analysis (CFA) models were fit and compared (Anderson & Gerbing, 1988); the hypothesized two factor measurement model with factors representing working memory and inhibitory control (Model 2), and the alternative measurement model consisting of one factor representing executive function (Model 1). The standard model fit indices used to assess Models 1 and 2 showed negligible differences. While there was no distinct solution based on fit indices, researchers and statisticians alike agree that while statistical criteria may be used to assess which model to choose, they should be interpreted more as guidelines regarding overall fit. Specifically, statisticians warn against treating such cutoff values as absolutes, such that "the reification of specific cutoff standards for the acceptance versus rejection of a hypothesized model can be fraught with peril" (West et al., 2012). Instead, the recommendation turns to selection based on theory rather than making modifications to the hypothesized models themselves. While there is literature to support both a one factor and two factor model, the goal of the current study is to investigate an interactive effect that is not possible within a one factor model. Therefore, the model containing two separate inhibitory control and working memory factors (2) was chosen for further analyses.

Prior to fitting a regression, it was important to contextualize gestures by first considering the influence of early arithmetic abilities. Here, another CFA was conducted to assess the structure of three latent factors; both inhibitory control and working memory latent factors from Model 2 with the addition of a factor of early arithmetic performance ("math") indicated by the proportion of correct responses in the Addition Strategy, Magnitude Comparison, and Symbolic Forced Choice tasks. Fit indices were again considered and deemed appropriate. Thus, the structure from model 3 was selected to undergo structural estimation procedures.

Using the identified factor structure from Model 3, a structural model was estimated to compare the relative strength of predictors to the outcome of children's gestures. Based on the hypotheses, directional pathways from two theoretical predictors (working memory and math) to gesture were estimated, while inhibitory control and gender (Aim 1) were set to covary with the outcome. Model fit indices as well as the significance of predictors and covariances were considered.

Aim 3. Lastly, prior work suggests inhibitory control may act as a gating mechanism by interacting with the flow of information in working memory during problem solving (Morrison et al., 2011), such that the indirect effect of inhibitory control on gesture would be positive (e.g., O'Neill and Miller 2013; Rhoads et al., 2018). Here, the hypothesis is that inhibitory control plays a moderating role in the relations between children's working memory abilities and their subsequent use of gesture during arithmetic problem solving (e.g., via better attentional control and slower decay of information; see Cowan et al., 2002). To test this updated version of the

GME model (Figure 2) of an interaction between latent variables inhibitory control and working memory on the outcome (gesture), a latent interaction variable was formed through the products of indicators for working memory and inhibitory control.

Product indicators were constructed using double mean centering (combined approach of residual centering and mean centering; Lin et al., 2010) and a matched pairs strategy using an automated function in the semTools r package (Jorgensen et al., 2021; Schoemann & Jorgensen, 2021). This resulted in a newly created factor for the interaction term (e.g., Interaction) indicated by the double mean centered product terms for Flanker by Backwards Span, Head Belly by Forward Span, and BRIEF IC by BRIEF WM scores. A new model was fitted following the factor and regression structure as Model 4, with the additional estimation of a pathway between the Interaction factor and outcome of gestures (Figure 14). Results pertaining to the model fit, covariance between factors, and significance of regression paths are discussed.

Power Analysis. The primary hypothesis of interest in this study is to see whether the effect of working memory on children's use of gesture during arithmetic problem solving is moderated by changes in their inhibitory control while controlling for correlated variables such as math and Age. Using the least parsimonious modeling possibility (a three-factor model with working memory, inhibitory control, and math as separate factors), an a priori power analysis was conducted using the root mean square error of approximation (RMSEA) index, as well as an effect = .05, alpha = .05, power = .80, df = 139 (SEMPower; Moshagen, M., & Erdfelder, E., 2016). Based on the recommended size, a sample of n = 136 was recruited.

Chapter 4: Results

Preliminary Analyses

Descriptive statistics were conducted to summarize how children performed on each measure and to assess if the study sample generally followed trends found in developmental literature. Pearson product-moment correlation coefficients (*r*) between all independent and dependent variables were calculated to determine the strength and direction of the variable (Table 7). As expected, age was significantly positively correlated with all math, working memory, and inhibitory control measures (*r*s between .23 to .73, all *p*s < 0.01). As expected, all inhibitory control measures were significantly, positively correlated with working memory and math (*r*s between .17 to .92, all *p*s < 0.05). Additional consideration of age and gender can be found in Aim 1.

Creation of Scaled Variables

The differences in scales in each independent variable necessitated variable scaling (see Table 3 for possible score ranges for each variable). Scale scores were calculated and used for all subsequent analyses (z-scores; Klopp & Klößner, 2021). Scaling the observed variables provides a more straightforward interpretation of the difference between parameter estimates, resulting in a clearer interpretation of the relations between latent variables.

Assessment of Multivariate Normality

An assessment of multivariate normality of the data was conducted for all predictor variables to determine which estimation method was most appropriate for the structural equation modeling. Multivariate tests of kurtosis and skew indicated some of the data are not multivariate normal (e.g., kurtosis > 7 for Flanker & Head Belly; skew < -.08 for Flanker, Head Belly, Magnitude Comparison, & Symbolic Forced Choice). Therefore, a robust version of the

Maximum Likelihood Estimation (robust ML) with robust standard errors and a Satorra-Bentler scaled test statistic was used to estimate and compare measurement models based on its suitability for complete, non-normal data (Rosseel, 2018).

Primary Analyses

Aim 1: To determine how children's inhibitory control, working memory, math, and gesture use varies by children's age and gender

Age. Children's age was calculated from the date they completed Session 1. The mean sample age was 5.90 years, ranging from the youngest at 4.10 years to the oldest at 7.82 years. As shown in Table 7, age was positively correlated with all measures of inhibitory control, working memory, and early math abilities such that older children performed higher on each measure than younger children (all significant positive correlations, *r*s ranging from .23 to .73). There was not a significant difference in the average age of male and female participants, M_{male} = 5.96 years and M_{female} = 6.01 years, $t(135) = -0.226$, $p = 0.822$, $d = 0.039$. Based on these and preliminary findings, children's age was included as a covariate in all subsequent models (1-5).

On average, 4-year-olds used 4.03 gestures ($SD = 4.414$), 5-year-olds used 2.315 gestures ($SD = 4.001$), 6-year-olds used 3.32 gestures ($SD = 3.951$), and 7-year-olds used 1.125 gestures ($SD = 2.511$). A visualization of children's gesture use by age group is available in Figure 8, and a descriptive statistics including means and standard deviations for each strategy type by Age can be found in Table 8. At first glance, gestures were only significantly, negatively correlated with children's age, $r = -.190$, $p = 0.028$. Linear regression analyses were conducted to assess how children's age and math performance both predict gesture, and whether there is an interaction between the two on children's use of gestures. Thus, individual regression analyses predicting gestures were conducted, including age, children's performance on each of the three math tasks

(Forced Choice, Addition Strategy, and Magnitude Comparison), and an interaction between the two. Results from each of the three regressions can be found in Table 9.

In line with prior research, age alone did not predict gesture in any of the models (all *p*s > 0.05). Instead, children's Forced Choice (Model A) and Addition Strategy performance scores (Model C) significantly predicted gestures. In both these models, the interaction for age by math performance scores showed a significant negative interactive effect (both *p*s <0.05). While the model for children's magnitude comparison scores did not reveal significant effects, results trended in the same direction such that magnitude comparison scores positively related to gestures ($\beta = 31.503$, $p = 0.058$), and the interaction with age was negatively related to gestures ($\beta = -6.084$, $p = 0.054$). These findings are in line with current developmental trends, suggesting the changes in gesture are not solely due to shifts in age but instead components of domain general and domain specific knowledge.

Gender. Next, children's gender in relation to children's gestures was next considered. The final sample ($n = 137$) was composed of 68 females (49.64%) and 69 males (50.36%). To determine if performance differences exist between genders on any of the measures, independent sample t-tests were conducted. T-test results as well as means and standard deviations for all tasks by gender are presented in Table 10. There were no gender differences present on children's working memory, inhibitory control, or math measures (all *p*s > 0.05).

To examine gender differences in the dependent measure (gestures), an additional t-test was conducted. Results showed a significant gender difference in gesture, such that females used significantly more gestures than males ($M_{female} = 3.60$ gestures vs. $M_{male} = 1.75$ gestures), $t(115.13) = 2.872$, $p = 0.005$, with $d = 0.489$, suggesting a small to medium effect size (small $d = 0.2$, medium $d = 0.5$; Cohen 1988). Gender differences in gesture use is presented in Figure 9.

An exploratory one-way ANCOVA was conducted to test if the difference in the use of gestures by gender was present, accounting for the effects of age. Results showed a significant effect of gender above and beyond the impact of age, $F(1, 134) = 8.728$, $p = .004$, $\eta^2 = 0.59$. The presence of the gender effect on the outcome necessitated the addition of gender as a variable in all subsequent models.

Gender by Age. Additional exploratory analyses of a gender by age interaction on gesture use was investigated using a two-way ANOVA. Main effects of age, $F(1,133) = 5.186$, $p = 0.024$, $\eta^2 = 0.037$, and gender, $F(1,133) = 8.713$, $p = 0.004$, $\eta^2 = 0.059$, on gesture use were significant, each with a small to medium effect size (Cohen, 1988). However, there was no significant interaction between age and gender, $F(1,133) = 0.155$, $p = 0.694$, $\eta^2 = 0.001$. Therefore, the addition of such an interaction variable was not included in the subsequent analyses.

Aim 2: To examine how children's concurrent inhibitory control, working memory, math, and use of gesture strategies are related, accounting for age and gender

In order to investigate the concurrent relations between inhibitory control, working memory, math, and the use of gestures, a verification of the appropriate factor structure for all observed variables was necessary. First, two confirmatory factor analyses (CFA) were run to compare whether measures of children's cognitive abilities were best suited to a one factor executive function model (Model 1), or an alternative two-factor model with separated factors for inhibitory control and working memory (Model 2). A comparison of fit indices for Models 1 and 2 was considered to determine which model best fit the sample data in terms of conceptualizing children's domain general abilities (either executive function in Model 1 *or* two distinct factors of inhibitory control and working memory in Model 2). Next, an additional CFA was conducted to assess the inclusion of a factor with all three predictors of math (Model 3). Then, a structural equation model predicting gesture was fit. Considerations of individual and compared model fit are discussed in a stepwise fashion (for a list of all models and fit indices, see Table 11).

To account for the additional measurement variation introduced by parent-measured variables of children's abilities (e.g., BRIEF working memory and inhibitory control scores are completed by the parent but represent children's working memory and inhibitory control), models allowed for covariation in these scores. For all CFA models (1-3), the goodness-of-fit indices for each model to the sample data were examined (see Hooper et al., 2008 for a review of guidelines of model fit). Table 11 outlines all subsequent CFA and SEM model fit indices.

Confirmatory Factor Analyses.

Model 1 CFA. Model 1 consists of one factor representing children's executive function indicated by standardized scores from the six executive function measures: Flanker, Head Belly, Backward Span, Forward Span, BRIEF IC, and BRIEF WM (Figure 10). Standard fit indices suggest Model 1 fits the data reasonably well, with $\chi 2$ (13) =27.060, p = 0.012, CFI=0.962, TLI=0.939, RMSEA = 0.089 with 90% CI [0.046,0.131], SRMR =0.063. All indicators loaded significantly onto the single executive function factor (all ps < 0.001) with Flanker = 0.371, Head Belly = 0.547, BRIEF IC = 0.734, Backward Span = 0.611, Forward Span = 0.303, and BRIEF WM = 0.806. Results indicate a one factor model of executive function could be an appropriate fit for the sample data well and forms a basis of analytical comparison for a two-factor model of inhibitory control and working memory (Model 2 CFA).

Model 2 CFA. Model 2 consists of two factors representing inhibitory control (indicated by Flanker, Head Belly, BRIEF IC) and working memory (indicated by Backward Span, Forward Span, and BRIEF WM). The results from measurement Model 2 are displayed in Figure 11. Standard fit indices suggest Model 2 also fits the data reasonably well, with $\chi 2(11) = 25.827$, $p = 0.007$, CFI=0.960, TLI=0.924, RMSEA = 0.099 with 90% CI [0.055, 0.144], SRMR =0.065. All indicators loaded significantly (all *P*s < 0.001) with inhibitory control indicators, with Flanker = 0.384, Head Belly = 0.548, BRIEF IC = 0.747, and working memory indicators, with Backward Span = 0.620, Forward Span = 0.294, and BRIEF WM = 0.815.

Due to comparisons of Model 2 results against the alternative one factor model (Model 1), the decision to retain a two-factor structure was made. While there were marginal differences in model fit between Models 1 and 2, the nature of the cutoff criteria is flexible in that they are created based on formulated data. In other words, the negligible differences in model fit necessitate model selection driven by theory in addition to statistics (Hancock & Mueller, 2013). Thus, the model that includes inhibitory control and working memory as separate factors was retained, and another CFA was fit to the sample data to assess whether the addition of a third factor relating to children's early arithmetic knowledge would be appropriate.

Model 3 CFA. Using the same loading structure for inhibitory control and working memory from Model 2, Model 3 was fitted with the additional factor of math, indicated by children's performance scores on Addition Strategy, Magnitude Comparison, and Symbolic Forced Choice tasks. Results from measurement Model 3 are displayed in Figure 12. Standard fit indices suggest Model 3 fits the data well, with $\chi 2(29) = 48.411$, $p = 0.013$, CFI= 0.968, TLI= 0.951, RMSEA = 0.070 with 90% CI [0.038, 0.099], SRMR = 0.056. Each of the three indicators loaded significantly onto a math factor (all *P*s < 0.001), with Addition Strategy = 0.972, Magnitude Comparison = 0.696, and Symbolic Forced Choice = 0.756. There was no change from Model 2 in the significance of loadings for inhibitory control or working memory factors (all *P*s < 0.001). Given good model fit indices and loadings, the structure of Model 3 was retained for the structural models.

Structural Equation Models (SEM).

Model 4 SEM. SEM was employed to measure and analyze the relationships of observed and latent variables. Specifically, based on current study hypotheses, working memory and math were regressed on the outcome, controlling for covariance due to inhibitory control, age, and gender. Using the identified factor structure from Model 3, directional pathways from working memory and math were regressed on the outcome (gesture; Figure 13). This model fit the data well, with $\chi 2(46)$=58.66.878, p = 0.024, CFI=0.0.968, TLI=0.070, RMSEA = 0.056 with 90% CI [0.026, 0.083], SRMR =0.058. There was no change from Model 3 in the significance of loadings for inhibitory control, working memory, or math factors (all *p*s < 0.001).

The predicted regression path between working memory and gestures showed the expected significant negative effect, β = -0.385, p = 0.011. The path between math and gestures showed a marginal positive effect, β = 0.249, p = 0.092. The covariance between gesture and inhibitory control was not significant, β = 0.008, p = 0.885, but in line with the detected effect, gender was a significant covariate, β = 0.248, p = 0.002. Age showed significant covariance with math, inhibitory control, and working memory factors (all *p*s < .001). Findings suggest that in models accounting for variance in children's inhibitory control, age, and gender, children's working memory was a significant negative predictor of their use of gesture, but their math knowledge was not. Possible interactive factors between working memory and inhibitory control are considered in Aim 3.

Aim 3: To test the role of inhibitory control as a moderator of the relations between children's working memory abilities and their use of gestures during arithmetic problem solving, controlling for age

A product indicator approach was taken to assess the moderating effect of inhibitory control on the path of working memory to children's use of gesture (Li et al., 1998). A new structural model was estimated (Model 5) to compare the relative strength of a product-based interaction term (henceforth "Interaction") between inhibitory control and working memory to the outcome of children's gestures, while also continuing to test for main effects of working memory and math (Figure 14). This model fit the data well, with $\chi2(72)= 95.092$, $p = .036$, CFI= 0.949, TLI= 0.925, RMSEA = 0.058 with 90% CI [0.019, 0.071], and SRMR =0.078. There was no change from Model 3 in the significance of loadings for inhibitory control, working memory, or math factors (all *p*s < 0.01). Simiar to the Model 4 regression findings, the main path from working memory to gesture use was significant, $\beta = - 0.477$, $p =0.009$. inhibitory control was not a significant covariate for gesture ($\beta = - .014$, $p = .788$). Gender was a significant covariate for gesture, $\beta = .243$, $p = .002$. Age showed significant covariance with math, inhibitory control, and working memory factors (all *p*s < .001). Conversely, Model 5 indicates that math also significantly predicts gestures ($\beta = .358$, $p = .047$). However, the hypothesized interaction effect of working memory and inhibitory control was not significant ($\beta = -0.111$, $p = 0.373$).

Even though the interaction path was not predictive, additional consideration regarding a model with, versus a model without, an interaction effect was necessary to determine retention of such interactions in later research. A chi-square difference test was conducted to compare Model 5 against a nested, null model where the interaction variable is restricted to 0 effect on the outcome. Here, a significant chi-square would indicate a retention of the Interaction variable.

Result suggests that there are no significant differences between the null model (no interaction effect) and the model when an interaction between inhibitory control and working memory is added (Model 5), $\chi^2(1) = 0.883$, $p = 0.347$. Taken together, results indicate that the interaction between working memory and inhibitory control is not predictive of gesture and should not be retained in future models. Thus, Model 4 (Figure 13) is selected as the parsimonious and predictive model of gesture.

Summary

Hypothesized relations in Aim 1 and Aim 2 were supported by the data, while those in Aim 3 were not upheld. Preliminary results suggested that measures chosen to include in the current study were developmentally appropriate, with a good distribution of scores for each and no floor or ceiling effects. The hypothesized effects for age on all variables were confirmed, and an unanticipated gender effect on the outcome of gesture was detected (Aim 1). Overall, the structural models considered fit the sample data well. Confirmatory factor analyses (Aim 2) confirmed the data could be fit with a one factor model pertaining to executive function (Model 1) or fit just as well by a model with separate factors for inhibitory control and working memory (Model 2). Given this consideration, and to consider the possibility of the adapted GME model (Figure 2), it was necessary to select Model 2’s structure to continue. The addition of the math factor, accounting for all early arithmetic measures, showed appropriate model fit indices (Model 3). The hypothesized predictive paths of children’s working memory, math ability was regressed onto the outcome, showing significant effects of working memory but not math (Aim 1). An additional, non-hypothesized path for gender was also included (based on significant gender effects in Aim 1), showing that this effect persists even with the inclusion of other factors. The predicted moderation model including an interaction between inhibitory control and working memory was not found (Aim 3). In sum, the current study provides empirical evidence that children's working memory and gender are requisite in the consideration of children's use of gesture in arithmetic contexts.

Chapter 5: Discussion

The goal of the current study was to investigate the concurrent relations between children's early mathematics knowledge, domain general cognitive abilities (e.g., inhibitory control and working memory), and their use of gesture during an arithmetic problem-solving task. Using the GME theoretical model of gesture use in math contexts (Gordon & Ramani, 2021) as a base, the relations of children's age and gender on each measured variable and the outcome (gestures) was investigated (Aim 1). Next, the study examined the structural relations of these factors and their impact on gesture use (Aim 2). Lastly, the hypothesized interaction effect between inhibitory control and working memory on gesture use was tested to examine potential extensions to the current GME model (Aim 3).

The current study extends prior work through the concurrent consideration of how children's domain general abilities (inhibitory control and working memory), math knowledge, and other individual factors (age and gender) contribute to their use of gesture in several ways. First, previous research has examined relations between two or three of these elements (e.g., math and executive function, see Bull & Espy, 2006; gestures and math, see Gordon et al., 2019; gestures, math, general "cognitive resources", see Goldin-Meadow et al., 2001). However, the current study is the first to evaluate the contribution of all these factors on children's gestures using structural equation modeling. This approach provides novel empirical evidence regarding the often-hypothesized convergence in factors across the fields of mathematics, executive function, and gesture research. In doing so, a critical gap in the literature is filled by providing an empirical test of suggested interrelations across these areas.

Second, this study expands upon current theoretical models of children's use of gesture in a math context (GME model, Gordon & Ramani, 2019) by directly testing a newly hypothesized interaction effect between working memory and inhibitory control while accounting for known covariates (Figure 2). While prior work often suggests that children's inhibitory control may directly impact children's ability to inhibit incorrect strategies and dominant responses (Borst et al., 2012; Linzarini et al., 2015), this study is the first to consider how the implementation of an embodied, gestural strategy is impacted. Given that children's inhibitory control levels correlates with developing math abilities (Agostino et al., 2010; Bull et al., 1999; Bull & Scerif, 2001; Khng & Lee, 2009; Passolunghi & Siegel, 2001; St. Clair-Thompson & Gathercole, 2006;; Swanson, 2006), the current study examined whether children's inhibitory control abilities was connected to their use of a particular type of strategy (e.g., gestures), while accounting for differences in cognitive and mathematical factors (e.g., Gordon et al., 2021). Critically, previous research supports an indirect impact of inhibitory control on gestures through a moderation of their working memory abilities. This hypothesis was based on work showing gestures' unique capacity to reduce users' cognitive demand, at least in part due to the users' ability to store relevant procedural or factual information on their fingers and hands during problem solving (Cook et al., 2012; Goldin-Meadow et al., 2001). The current study tests this extension of current work and provides evidence to support the retention of the original GME model (Gordon & Ramani, 2021).

Investigating Relations Between Inhibitory Control, Working Memory, Math, and Gestures

Overall, children's age shared a significant, positive relation with all measures of working memory, early mathematics performance, and inhibitory control . These findings are in line with current research showing that children's age positively relates to their working memory (e.g., Gathercole et al., 2004), inhibitory control (Christ, 2001), and math abilities (e.g., Geary 1994). Furthermore, we found positive correlations between working memory and arithmetic performance (Bull & Espy, 2006). In line with the study hypotheses, children's age was negatively related to their use of gestures such that younger children use more gestures than older children while solving arithmetic problems. This finding follows current research, such that as children grow older, they tend to shift towards using more advanced, mental calculation-based strategies (Huttenlocher et al., 1994; Siegler, 1996).

Unlike age, there were no gender differences in children's performance on all indicator variables for inhibitory control, working memory, or math. However, there was a significant difference in the outcome, such that females used almost twice as many gestures than males during the arithmetic problem-solving task. While gender differences were not expected, , this effect was accounted for in all models of gesture use. Above and beyond the impact of other influencing variables, this gender effect remained significant. As such, further discussion is warranted regarding the inclusion of gender when modeling the use of gesture in a mathematics environment. Additional consideration of the role of gender on gestures as well as a brief post-hoc review of gender within mathematical contexts is considered (See Future Directions).

Cognitive Influences on Children's Use of Gestures

Overall, the findings of the current study provide evidence that children's domain general and domain specific math abilities relate to their use of gesture during an arithmetic task. In the current study, children's domain-general abilities were fit to the hypothesized two factor model of working memory and inhibitory control. Models with distinctive variables for each of these factors are supported within the current literature (Miyake et al., 2000). In line with study hypotheses, results highlight the unique contribution of working memory on the use of gesture, above and beyond other possible predictors (e.g., math, gender) while accounting for the variation within inhibitory control and age. Here, children with a lower working memory used more gestures than their peers with a higher working memory. These findings are in line with prior work showing that young children use gestures strategically in tasks which pose explicit working memory demands (Delgado et al., 2011), as well as research showing how children with higher working memory opt to use mental strategies such as retrieval (Barrouillet and Lépine, 2005). These findings support the original theorized GME model (Figure 1, Gordon & Ramani, 2021), suggesting that children who have less cognitive resources available to them (e.g., smaller working memory span) may rely more heavily on strategies which allow for a re-allocation of the cognitive burden (e.g., gestures, an embodied strategy). Importantly, while an unanticipated effect of gender on the outcome of gesture was found, working memory was retained as a significant predictor.

Interactive Influences on Children's Use of Gestures

The central hypothesis of the current study was that an interaction between inhibitory control and working memory abilities would account for variation in children's use of gestures. Specifically, individual differences in inhibitory control moderated the relation between children's working memory (e.g., the processes by which children's procedural and factual math knowledge is used during problem solving), and the outcome of the explicit use of a gesture strategy. However, assessment of a structural equation model with the inclusion of such an interaction yielded no such significant effects (Aim 2). Despite the lack of a hypothesized interaction effect, children's working memory still predicted gesture use above and beyond all other included variables. Thus, the proposed adaptation (Figure 2) to the original GME model cannot be recommended based on sample data; it strengthens the claims made in the initial GME model (Figure 1).

While children's gesture use is not significantly related to their inhibitory control, further consideration of the cognitive factors beyond working memory may provide a more comprehensive understanding of the mechanisms driving gesture use during math contexts. Prior work suggests that younger children (who typically lack additional relevant procedural knowledge) use prepotent strategies from previously learned math content, such as counting (Overlapping Waves Model, Siegler, 1996). While the current study hypothesis of an interactive effect between inhibitory control and the procedural and strategic information manipulated in working memory was not found, these results do not negate the possibility of such an interaction across other mathematical domains or ages, nor does it act as confirmation of the null hypothesis. Instead, it suggests that we cannot draw conclusions regarding the presence of an interaction effect from the current sample within simple arithmetic problems only. Moreover, the discovery of such a "null" result is important, and should not be disregarded (e.g., the file drawer problem; Rosenthal 1979). It may lead to additional research questions in the future. For example, future researchers should consider questions rooted in what factors beyond working memory drive observed differences in children's strategy use (e.g., gesture or others). Thus, simultaneously modeling the relation between cognitive factors, such as attention, which share variance with working memory could allow for better insight into the unique relation between working memory and gesture use.

Gender Effects Imply a New GME model

The gender differences found in the present study suggests the possibility that a revised GME model is needed. Analyses revealed significant gender differences in gesture use such that females used more gestures than males. While the current study did not anticipate gender as a consequential predictor in gesture use, these findings do align with some studies relating to mathematical strategies more broadly. Research suggests that males and females vary in their types of strategies used during arithmetic problem solving. Specifically, findings indicate that males use more mental strategies than females (e.g., retrieval; Carr & Davis, 2001; Carr & Jessup, 1997; Bailey et al., 2012), which could explain why males showed less gesture strategies than their female peers.

Research regarding the presence of sex differences[3] in gesture use can be found in the field of child language development as well as neuropsychology. Prior work suggests that female infants show an advanced trajectory of speech progressions (e.g., single to multi-word utterances) through the combination of speech and gesture (Özçalışkan & Goldin-Meadow, 2010). This finding suggests that, from a young age, females may tend to use gestures when it is developmentally advantageous for them (e.g., in situations which require newly learned, higher level sentence structures, or in the present study during arithmetic tasks). Neuropsychological findings provide additional evidence that preschool-aged females may have an advantage in the imitation of gestures. For example, when asked to imitate single or multiple gestures (both non-

[3] Discussion of sex (biological) and gender (societal) construct differences are discussed together. Importantly, neither sex nor gender are a binary constructs, and as such they can interact differently over time.

representational and common everyday gestures), females had significantly fewer errors relevant to the gesture construction and meaning (e.g., praxis) than their male counterparts. The presence of gender differences favoring females across different domains of research related to gestures highlight the possibility that this is a persistent effect that bears future consideration.

In addition, it is necessary to further consider how gender effects on mathematical procedures and outcomes could be realized in the form of differential gesture use. Past research has shown gender effects on the interrelations between children's mathematics performance and general cognitive skills. Specifically, males tend to rely more on their spatial reasoning abilities, while female's math performance relates to their verbal skills (Klein et al., 2010).These differential trends suggest that during problem solving, children may rely on distinct processes depending on their gender. Given that males seem to employ more spatial reasoning, the use of an embodied strategy to reduce cognitive efforts may not be needed. On the other hand, in the instance that females are reliant on more verbal abilities, they may need to lean on external strategies like gestures, in turn offloading additional spatial resources.

Moreover, children show autonomy in the choice of strategy they opt to use during arithmetic problem solving (Carr & Davis, 2001). Specifically, there seem to be differences based on their own preference, what they have been taught to use in school by teachers or at home by their parents, their motivation, and their conceptualization abilities. These additional factors could account for divergences in the use of gesture between males and females.

While unanticipated, the combination of support from prior literature and results from the current study supports a modification to the original GME Model, whereby gender is included as a factor that may influence children's use of gesture (Figure 15). Implications regarding the inclusion of gender as a variable of interest in future studies is considered (See Future Directions).

Limitations

There are several notable limitations to the current study. First, the sample was limited in the diversity of participating families' socioeconomic status, with over 50% of parents completing at least a 4-year college degree, and 50% of families having over $100,000 in yearly income (see table 2). Without a representative sample of families from broader backgrounds, it is not possible to extrapolate the findings of this study to a diverse population. Additional consideration of how new studies could address this issue is included in the future directions. Second, the study did not include a comprehensive measure of the schooling children received. While children's age is accounted for, it is important to note that children's individual birth date impacts the grade they may currently be enrolled in depending on age-related school entrance cutoffs. Prior research has shown that 6-year-old children whose date of birth allowed them to enroll first grade showed higher performance on short-term memory and quantitative tasks compared to their same aged peers who missed the cutoff and were thus enrolled kindergarteners (Bisanz et al., 1995; Christian et al., 2001). Thus, future studies should consider not just age, but the possibility that differences in schooling duration and experiences may impact children's outcomes for early math as well as general cognition (e.g., working memory and inhibitory control).

A number of these relate to the nature of constraints on developmental studies still necessitated by the global Covid-19 pandemic. Critically, all testing sessions were conducted via virtual platforms; Gorilla.sc for session 1, and over Zoom for session 2. Although conducting virtual studies allows for recruiting families from a broad geographical area, participation required that a family had access to a device that was connected to the internet. Such technology-based study requirements meant low accessibility to families who may not have such resources in their home. Future research could navigate this issue by focusing funding efforts on providing or lending such technology to participating families.

Across the two sessions, there was the possibility of high variability in testing conditions. Children were at risk of being exposed to distractions from external influences, leading to variation in their motivation as well as their ability to concentrate during each session. Families were instructed to complete session 1 on their own at a time that was convenient for them, which opened the possibility for variation in the time of day that sessions 1 and 2 were completed.

Furthermore, there were differences in the settings where children were able to complete their second session due to the remote nature of testing. These locations included indoor and outdoor spaces, sometimes accompanied by their parents or other family members while others completed the session alone. If a parent or older sibling were in the room, they may have felt compelled to assist the participant and provide hints. While experimenters were trained to consistently ask these family members to allow children to complete the session independently, oftentimes this would be after they already attempted to provide feedback to the child. As such, it is possible that some participants faced distractions that would not be present in a more controlled testing environment. In the case of in-person testing, the participants are often working one-on-one with an experimenter and such intrusions are much less likely to occur.

Related to the setting, differences in technology may have also impacted children's performance, especially during the second session. For example, children had the option of participating via any internet connected device, meaning they may have viewed the study measures for session 2 on a computer, tablet, or phone screen based on the availability of such resources within the home. Viewing stimuli on screens of various sizes meant that children may not have had a uniform study experience. Those who participated on smaller devices may have encountered issues seeing the digital stimuli details.

However, thoughtful efforts were taken in the study design to ensure all children who were able to participate had an equal opportunity to answer all questions to the best of their ability. Specifically, audiovisual checks were implemented in Session 1 that parents completed to ensure proper setup of the computer. Furthermore, both sessions contained audio information either from a recording or live from an experimenter, to mitigate any possible issues in visual display, or differences in reading/numerical comprehension to curb limitations from visual representations. At the start of session 2, experimenters followed a protocol to ensure that all children were positioned comfortably and in view and performed audio/visual checks to ensure there was no screen lag throughout the experiment itself. Thus, while the nature of online testing posed recruitment challenges, numerous steps were taken to ensure participants all were able to complete the study.

Future Directions

Future work should expand upon the findings of the current study. Specifically, additional work considering these results across measures of gestures, various math domains, the role of social influences on both mathematics and gesture, and the generalizability of the revised GME model (Figure 15) to a global population is necessitated.

Different Measures of Gestures

In the current study, children's use of gestures are considered holistically, such that children receive a score of the number of times they used a gesture based strategy across their arithmetic problem solving. While this measure is appropriate in scope for the study at hand, there are other ways to categorize and inspect gesture use that may be used to uncover additional, related research questions. For example, many studies have used speech-gesture mismatch to consider how children's speech and gesture content align (e.g., Church, & Goldin-Meadow, , 1986; Perry et al., 1988; Broaders et al., 2007**)** In other words, when a child uses both gesture and speech to solve a particular problem, experimenters would rate whether the information contained in their speech "matches" with the information contained in their gesture. This provides additional insight into whether a child knows relevant procedural or factual mathematics information, but perhaps may not yet be able to verbalize it. Future studies could employ match/mis-match coding schemes to investigate how and when these may occur during arithmetic problem solving, and answer additional research questions pertaining to how they may further relate to differences in inhibitory control and working memory.

Math Anxiety

An additional factor which could influence children's strategy use and subsequent performance is math anxiety, defined as the feelings of apprehension and fear when dealing with numerical information (Maloney & Beilock, 2012). Future researchers interested in connections between math anxiety and performance could consider how individuals use gestures within the context of the revised GME model. Research shows that math anxiety is influenced by numerous cognitive factors, and ultimately plays a significant role in math learning and performance (e.g., Chang & Beilock, 2016). Behavioral and neurological evidence suggests that these connections are due in part to working memory resources being mis-allocated to negative thoughts and ruminations about math, rather than being directed towards the math content itself (Behavioral: Ashcraft & Kirk, 2001; Park et al., 2014; Neurological: Young, Wu, & Menon, 2012; Lyons & Beilock, 2012). Moreover, math anxiety interacts with working memory, such that those with higher working memory show a greater negative effect on their subsequent math achievement (Ramirez, Gunderson, Levine, & Beilock, 2013; Vukovic, Kieffer, Bailey, & Harari, 2013). Relatedly, children's math anxiety is a negative predictor of using higher level problem-solving strategies especially for those children with larger working memory (Ramirez et al., 2016). Taken together, these results suggest that math anxiety may serve as both an indirect contributor (through the reduction of working memory resources and math learning), as well as direct influence (suppressing certain types of strategies) on children's use of gesture.

Lastly, math anxiety may have shaped the gender related findings of the current study. Specifically, results indicated a gender difference in modality of strategy used (females use more gestures). This may at least in part be explained by the intersection of gender and math anxiety. Prior research suggests that primary and school-aged females experience higher levels of math anxiety, and these elevated levels lead to poorer math performance (Devine et al., 2012; Hill et al., 2016;). While the current study does not show differences in math performance, the difference in gesture may be accounted for due to females falling back on a strategy that, when used appropriately, leads to reliably accurate results.

Math-gender stereotype influence

Given the presence of a gender effect on gesture in the current study, additional social influences should be considered going forward. One such influence is math gender stereotypes, which are implicit assumptions that females overall are less capable in the field of math (for a review of gender stereotypes, see Ellemers, 2018). Math gender stereotypes are observed among children as young as age six and become more prevalent throughout adolescence (Cvencek et al., 2011). Perhaps more concerningly, the prevalence of this internalized stereotype better predicts children's overall academic achievement and enrollment preference for math courses than females' explicit attitudes about gender and math (Steffens et al. 2010). It is possible that the internalization of such stereotypes influences the use of gesture strategies by gender. For example, males may opt for mental math type strategies more often in contexts where they are being observed, to show that they are more advanced. Females however may find themselves showing an over-reliance on naive strategies (like finger counting during arithmetic), as they feel as if they are not as good at math. Future research is needed to consider how math-gender stereotypes may influence gestures in arithmetic contexts, as well as for the gestures during higher-level math environments for older children (e.g., Fractions; Edwards, 2009). Consideration of such possibilities is essential to flesh out additional social factors that could influence the use of gesture within a broader mathematical context.

Math Domains

Future research beyond arithmetic is necessary to consider the applicability of GME to various domains of mathematics. While some research has been conducted in more elementary math (e.g., knowledge of cardinality; Gordon et al., 2021), there is a lack of current research focusing on gestures relation to cognitive factors within higher level mathematical contexts. While some studies have considered how adults learn new mathematical concepts with the support of gestures (see Aldugom et al., 2022), or use gestures in a collaborative problem-solving context (Reynolds & Reeve, 2001), or while explaining difficult math problems to children (Flevares & Perry, 2001). However, there is a lack of consideration given towards the relations between underlying cognitive factors (e.g., inhibitory control, working memory, as well as domain specific math knowledge) in studies testing children on their use of gesture. The addition of studies which employ an analytical approach similar to the current study would be better enabled to speak to the mechanisms underlying adults' use of gesture within math contexts.

Generalizability in a global context

Research within the domain of gesture and language highlights another consideration; that across languages, there is a wide variety of how certain concepts may be expressed both verbally and gesturally. In David McNeil's seminal work (1992), he theorized that speakers plan their speech using both mental imagery as well as linguistic thinking. Thus, when speakers are in a mathematical context, their thought process will involve pieces of linguistic information that is unique to their language as well as more universal spatio-motoric imagery (relating to movement through space) related to the math content they are discussing. Cross-linguistic work suggests similarities in adults' gestures, spatial thinking, and speech (Kita & Özyürek, 2003); however, more research regarding how the language of speakers may change the quantity or quality of gestures in math specific contexts.

Lastly, to fully understand the applicability of the GME model to a broader population, it is necessary to conduct additional research with samples from populations where mathematics performance is higher. In an international comparison of mathematics performance scores, a gap of almost three years was found between Massachusetts and the top performing locale included in the study, Shanghai, China (OECD 2012). Thus, without additional research considering how children who would follow an approximately similar development for domain general abilities while simultaneously tracking at a higher level of mathematics, it is not possible to discuss the robustness of the relations in the current study. Future work should consider modeling these effects for children at a stable level of mathematics knowledge, but at various levels of domain-general knowledge, age, and area of schooling on a global scale.

Implications and Applications

The current study provides novel insight into how children's use of gesture strategies may be shaped by their underlying cognitive skills and knowledge. Children's employment of different strategies during early math contexts is often used as an indicator of math procedural knowledge, however there is limited research examining how the use of an embodied strategy such as gesture may be more tenuous based on cognitive abilities. Findings from the current study support the consideration of children's working memory specifically during the assessment of gesture-based strategies.

Intervention-based research supports the notion that gesture is effective in bolstering mathematics learning (e.g., Congdon et al., 2017), and even enhancing broader STEM contexts (e.g., improving spatial thinking; Stieff et al., 2016). While gesture has not always been encouraged in classroom settings, instructors should consider how gesture could be especially useful during problem solving. Additionally, the current study's support of the link between working memory and gesture highlights that children who have larger working memory use gesture less often. However, that is not to say that children with higher-than-average working memory abilities could not also benefit from the use of gesture instruction. By specifically highlighting relevant mathematical information using hand gestures, children of various cognitive abilities could glean insight into new concepts. Indeed, research supporting that children spontaneously gesture more when they are on the cusp of learning something new suggests that increasing gesture at this time could assist with acquisition of novel ideas (Goldin-Meadow, 2009).

A more expansive view on the application of gesture can be applied to the home-learning environment. Encouraging caregivers and children alike to use gestures in a comfortable environment may drive later use of gestures in school contexts where students may be more prone to social and math anxieties which deter the use of embodied practices. Furthermore, research suggests that successful interventions are often those that are flexible and use a strength-based approach for a diverse population of families (Eason et al., 2020). Providing families with the knowledge that gestures could perhaps be one of the most readily accessible and freely implementable tools currently available for learning.

Specifically, providing children with explicit instruction to use gestures may be especially beneficial for children from lower-income backgrounds. Children from low-income backgrounds' early mathematical knowledge lags behind their same-age peers from middle- to upper-income families (Ramani & Siegler, 2011; Starkey, Klein, & Wakeley, 2004). These differences only continue to grow over time (Denton & West, 2002; McClelland, Acock, & Morrison, 2006), highlighting the need for early intervention with readily available tools. As such, the encouragement and education related to the use of gesture in math contexts could support a wide array of math learners.

Conclusion

Children's use of gestures as a tool during mathematical contexts has been shown to lighten working memory load and boost math learning. However, much of the current research does not consider how individual differences in inhibitory control, working memory, and math knowledge simultaneously impact the use of such a strategy. The current study provides novel evidence that in models of gesture use, working memory stands out above and beyond other cognitive abilities, such as inhibitory control and relevant mathematical understanding. Furthermore, the study provides additional insight into how gender may shape children's use of gesture. A newly proposed model of Gesture in Mathematical Environments highlighting the role of working memory and the implication of gender is proposed for future research.

Tables and Figures

Table 1

Sample Count (n) of Children's Age by Gender

	Female	Male
4 years old	16	14
5 years old	17	21
6 years old	19	18
7 years old	17	15
Total	69	68

Table 2

Descriptive Statistics of Demographic Survey Variables from Respondents (Total Sample n = 137)

	n respondents (total *n* = 130)
Child Race, *n* (%)	
Asian or Pacific Islander	28 (21.5 %)
Caucasian/white	80 (61.5 %)
American Indian or Alaska Native	2 (1.5 %)
Biracial/Mixed Race	16 (12.3 %)
African American or Black	1 (0.8 %)
Other [a]	3 (2.3 %)
Child Ethnicity, *n* (%)	
Hispanic or Latino	12 (9.2 %)
Not Hispanic or Latino	118 (90.8%)
Parent 1 Education, n (%)	
Some high school coursework	0 (0%)
High school diploma/GED	4 (3.1%
Some college coursework/vocational training	8 (6.2%)
2-year college degree (Associates)	6 (4.6%)
4-year college degree (BA/BS)	50 (38.5%)
Postgraduate or professional degree (MA, PhD, MD, JD)	6 (47.7%)
Parent 2 Education, n (%)	
Some high school coursework	1 (.8%)
High school diploma/GED	8 (6.2%)
Some college coursework/vocational training	9 (6.9%)
2-year college degree (Associates)	8 (6.2%)
4-year college degree (BA/BS)	35 (26.9%)
Postgraduate or professional degree (MA, PhD, MD, JD)	55 (42.3%)

Missing	14 (10.8%)
Annual Household Income, n (%)	
Less than $20,000	1 (.8%)
$20,000 to $34,999	1 (.8%)
$35,000 to $49,999	6 (4.6%)
$50,000 to $74,999	24 (18.5%)
$75,000 to $99,999	21 (16.2%)
Over $100,000	72 (55.4%)
Missing	1 (.8%)

[a] *"Other" Races input by caregivers included Pakistani American and Hispanic*

Table 3

Summary of task details

Task	Session	Dependent Variable(s)	Possible Range	Sample Range	Factor
BRIEF 2/BRIEF P	-	Inverse Working Memory Raw Score	-100 to 0	-44 to -8	Working Memory
		Inverse Inhibitory Control Raw Score	-100 to 0	-46 to -8	Inhibitory Control
Flanker	1	Inverse Reaction Time Cost	Participant response time dependent	-3847.300 to 1361.954	Inhibitory Control
Head Belly	2	Trials Correct /16 total trials	0 to 1	0 to 1	Inhibitory Control
Forward Span	2	Highest Span Correct	0 to 7	1 to 6	Working Memory
Backward Span	2	Highest Span Correct	0 to 7	1 to 5	Working Memory
Forced Choice	1	Trials Correct /6 total trials	0 to 1	0 to 1	Math
Magnitude Comparison	1	Trials Correct /18 total trials	0 to 1	0.33 to 0.875	Math
Addition Strategy	2	Trials Correct / 12 total trials	0 to 1	0.2 to 1.0	Math

Table 4

Order of Trials and Responses for Head Belly Task

Trial #	Read to the child by experimenter	Correct response from the child
1	Head	Belly
2	Belly	Head
3	Belly	Head
4	Head	Belly
5	Belly	Head
6	Head	Belly
7	Head	Belly
8	Belly	Head
9	Belly	Head
10	Head	Belly
11	Belly	Head
12	Head	Belly
13	Belly	Head
14	Head	Belly
15	Head	Belly
16	Belly	Head

Table 5

List of problems for children to solve in the modified Addition Strategy Task

Problem	Solution	Smaller number presented first	Sum above 10	Example problem with feedback
2+2	4	n/a		x
4+3	7			
5+3	8			
9+4	13		x	
3+6	9	x		
7+3	10			
6+8	14	x	x	
2+5	7	x		
4+2	6			
7+4	11		x	
5+6	11	x	x	
4+5	9	x		
10+5	15		x	

Table 6

Description of math strategies used by children to solve problems in the modified Addition Strategy Task by modality

Math Strategy	Description	Modality		
		Gesture	Verbal	Gesture & Verbal
Minimum	Started at highest number and counted up	X	X	X
Maximum	Started at lowest number and counted up	X	X	X
Sum	Started at zero and counted the sum of the two digits	X	X	X
Not Specified	Saying numbers /holding up fingers in a random order, or mouth moments are seen but are inaudible	X	X	X
Offscreen	Appears that they are watching their fingers move but they are not fully in the video	X	-	X
Total	Holds up the total sum of fingers all at once	X	-	X

Table 7

Descriptive statistics including means, standard deviations, and correlations for all variables

Variable	*M*	*SD*	1	2	3	4	5	6	7	8	9	10
1. Age	5.98	1.07										
2. Flanker	-217.51	588	.31**									
3. Head Belly	0.89	0.2	.45**	.19*								
4. BRIEF IC	-18.86	7.51	.68**	.31**	.41**							
5. Forward Span	4.28	0.98	.23**	.23*	.30**	.17*						
6. Backward Span	2.58	0.7	.53**	.29**	.43**	.33**	.38*					
7. BRIEF WM	-19.14	8.37	.73**	.29**	.45**	.92**	.17	.43**				
8. Forced Choice	0.84	0.21	.52**	.27**	.30**	.43**	.09	.34**	.43**			
9. Magnitude Comparison	0.77	0.13	.53**	.30**	.34**	.34**	.26**	.42**	.46**	.47**		
10. Addition Strategy	0.66	0.38	.64**	.29**	.38**	.48**	.28**	.48**	.56**	.75**	.68**	
11. Gesture	2.69	3.89	-.19*	.07	.01	-.15	-.12	-.16	-.16	.02	-.10	-0.05

Note. M and *SD* are used to represent mean and standard deviation, respectively. * indicates $p < .05$. ** indicates $p < .01$.

Table 8

Descriptive statistics including means and standard deviations for each strategy type by Age

	Gesture		Mental		Verbal		Other	
	M	SD	M	SD	M	SD	M	SD
4 year olds	4.03	4.41	6.67	4.47	0.53	1.36	0.77	1.87
5 year olds	2.32	4.00	8.92	4.25	0.71	2.01	0.05	0.23
6 year olds	3.32	3.95	8.51	3.90	0.11	0.32	0.05	0.23
7 year olds	1.12	1.12	10.70	2.82	0.13	0.42	0.03	0.18

Table 9

Regression Analysis Coefficients predicting Gesture by Age, math task performance variable, and an interaction between the two

	Model A	Model B	Model C
(Intercept)	-13.169	-18.065	-1.873
Age	2.632	4.172	0.899
Forced Choice Performance	25.227*		
Interaction: Forced Choice x Age	-4.102*		
Magnitude Comparison Performance		31.503 .	
Interaction: Magnitude Comparison x Age		-6.084 .	
Addition Strategy Performance			15.4107 **
Interaction: Addition Strategy x Age			-2.609*
R2	0.09	0.06	0.09

All continuous predictors are mean-centered and scaled by 1 standard deviation. ** $p < 0.01$; * $p < 0.05$., . $p < 0.06$

Table 10

Means, standard deviations, and t tests for all measurement variables by Gender

Factor	Variable	*Male M*	*Male SD*	*Female M*	*Female SD*	t	df	*p*	d
-	1. Age	5.963	1.053	6.005	1.098	-0.226	134.9	0.822	0.04
Inhibitory Control	2. Flanker	-227.090	594.351	-208.074	585.878	-0.188	134.9	0.851	0.03
	3. Head & Belly	0.841	0.225	0.907	0.166	-1.341	123.15	0.182	0.23
	4. BRIEF/2 IC	-19.367	6.856	- 19.362	8.140	-0.781	130.55	0.436	0.13
Working Memory	5. Forward Span	4.279	0.895	4.246	0.976	0.206	134.31	0.836	0.04
	6. Backward Span	2.647	0.824	2.507	0.851	0.977	134.96	0.330	0.17
	7. BRIEF/2 WM	-19.485	8.665	-18.797	8.127	-0.479	134.17	0.633	0.08
Math	8. Forced Choice	0.838	0.206	0.851	0.209	-0.354	135	0.724	0.06
	9. Magnitude Comparison	0.785	0.106	0.750	0.150	1.573	122.7	0.118	0.27*
	10. Addition Strategy	0.668	0.384	0.642	0.389	0.384	135	0.701	0.07
-	Gestures	1.750	2.867	3.609	4.535	2.867	115.13	0.005**	0.49*

Note. M and *SD* are used to represent mean and standard deviation, respectively. * indicates $p < .05$. ** indicates $p < .01$.
* = small *d* (~0.2) ** = medium *d* (~ 0.5); Cohen 1988

Table 11

Fit indices for confirmatory factor analyses and structural equation models

Model	Description	χ^2	DF	*p*	CFI	TLI	RMSEA	SRMR
1	CFA: Scaled one factor EF	27.060	13	0.012	0.962**	0.939*	0.089*	0.063**
2	CFA: Scaled two factor IC & WM	25.827	11	0.007	0.960**	0.924*	0.099*	0.065**
3	CFA: Scaled three factor IC, WM, & Math	48.411	29	0.013	0.968** +	0.951**+	0.070*+	0.056**+
4	SEM: Model 3 structure + regression	66.878	46	0.024	0.969	0.955	0.058	0.058
5	SEM: Model 3 structure + regression with interaction	95.092	72	0.036	0.949	0.925	0.048	0.078

*EF = Executive Function, IC = Inhibitory Control, WM = Working Memory; * = acceptable, ** good, + = comparative best*

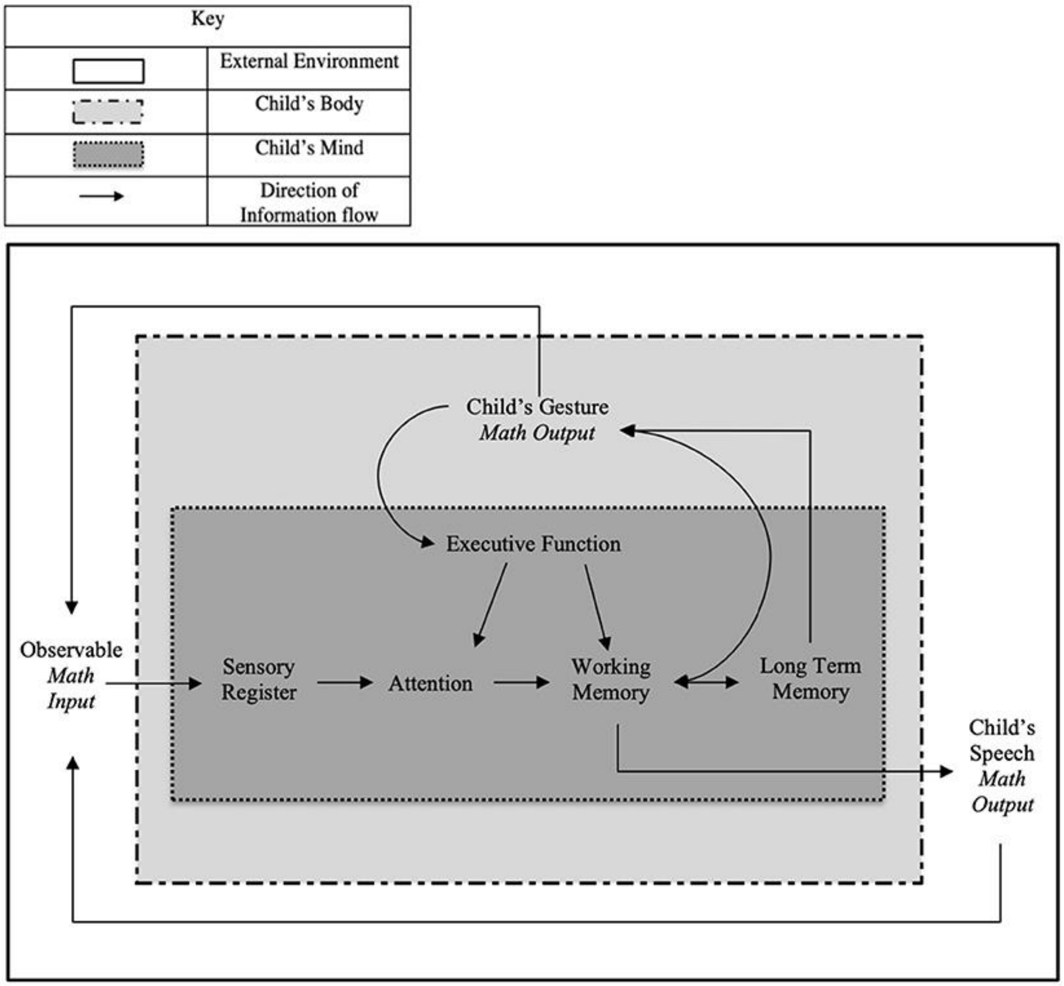


Figure 1. Conceptual model of the role of gestures in mathematical environments (GME model; Gordon & Ramani 2021)

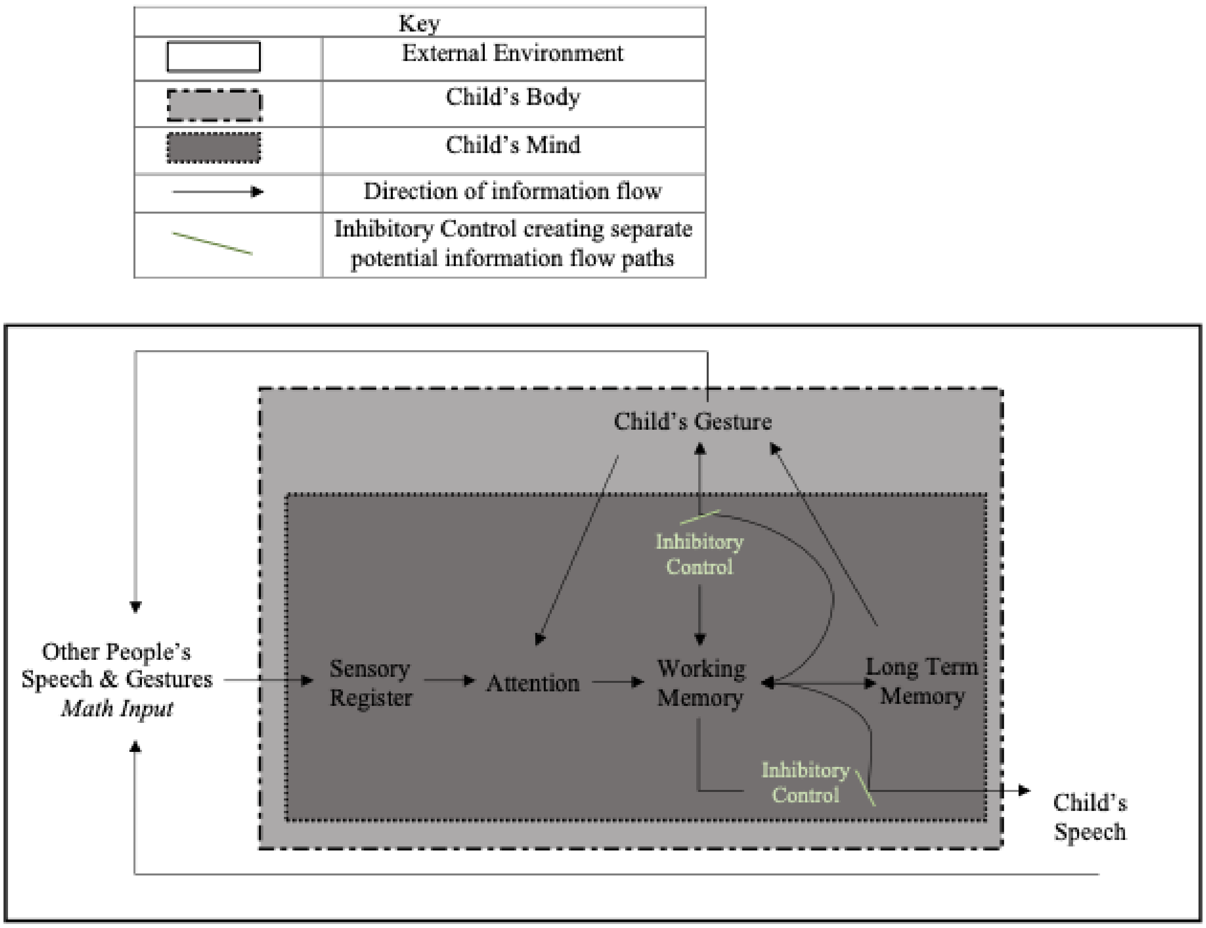


Figure 2. The proposed modified version of the GME model with inhibitory control as a moderator

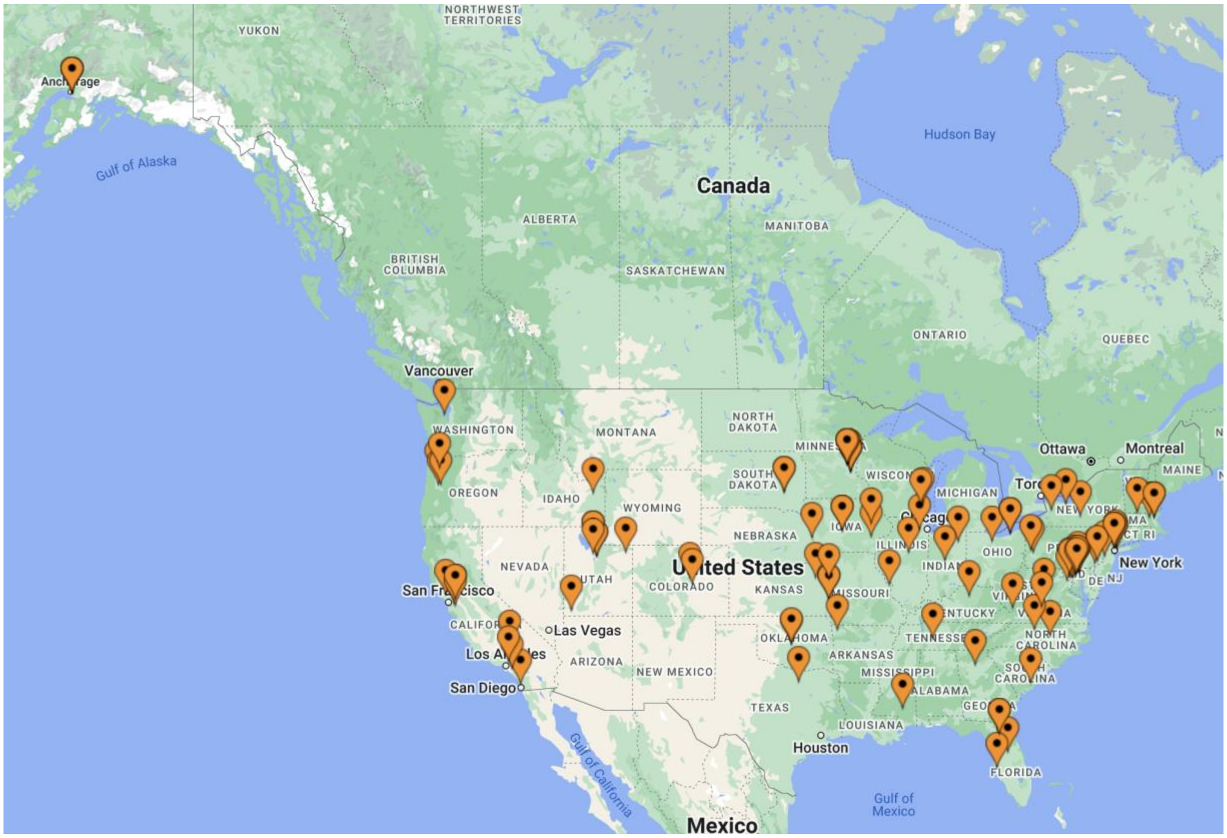


Figure 3. Map of participant geographic locations. Participation was limited to participants living in the United States (n=137)

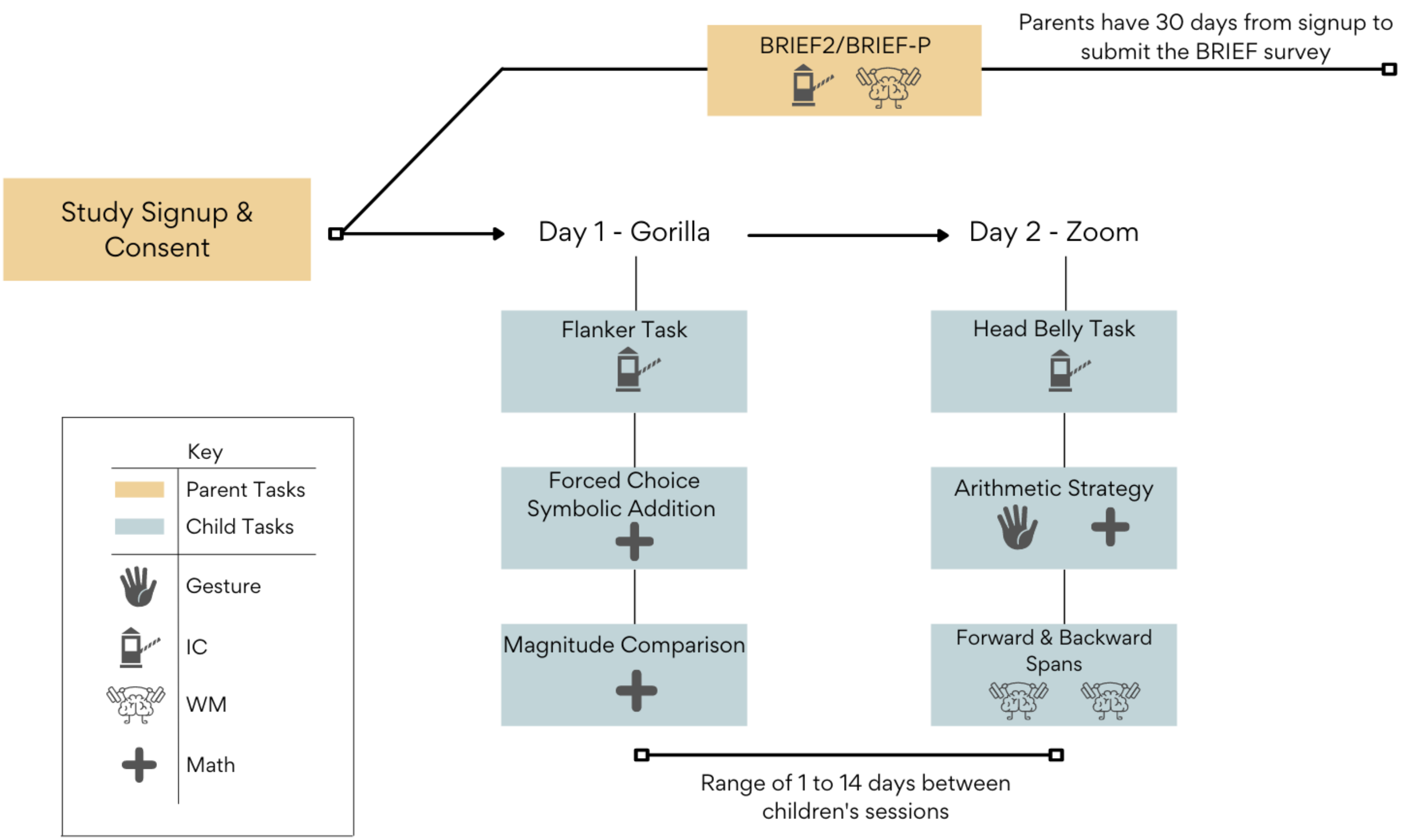


Figure 4. Flowchart of all study measures. The flow begins on the left, with the color of the task denoting who completes the task, and a symbol representing which construct the task is assessing.

Figure 5. Screen capture of image children are shown during keyboard training for learning to press the "a" and "l" keys

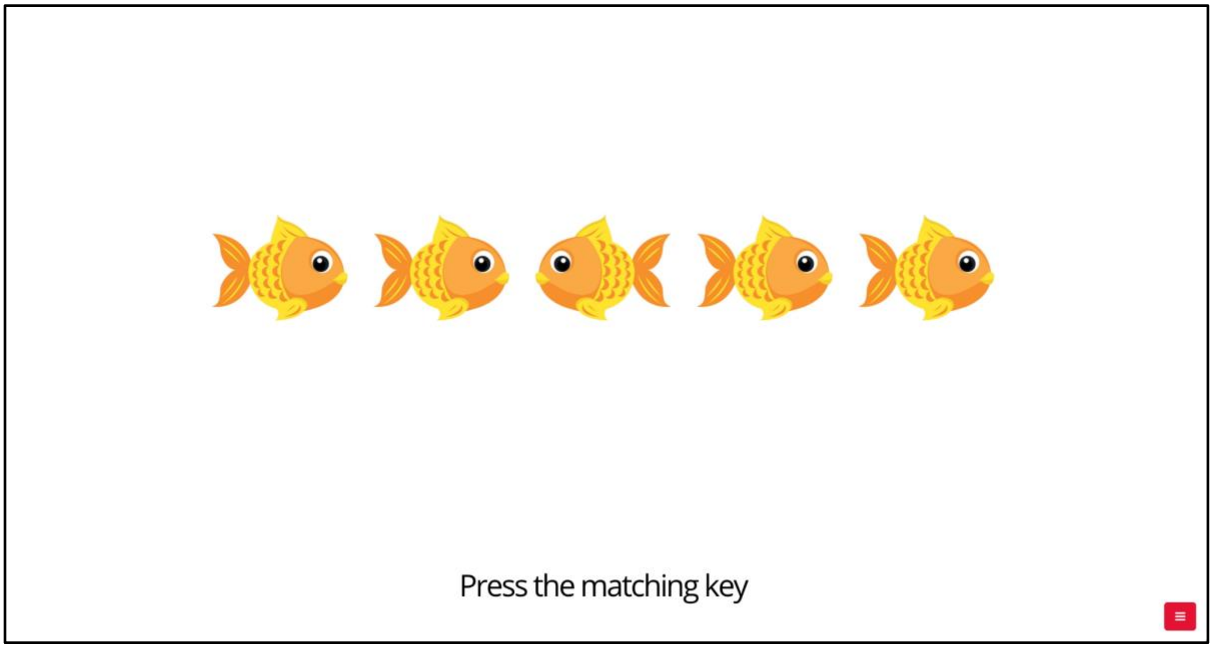


Figure 6. Screen capture of Flanker test trial during which the correct response key is “a” for the middle fish facing to the left.

Figure 7. The top left picture displays the introduction to the "game" titled "Math Adventure", the top right picture depicts an example of a problem display a child would see, and the bottom picture shows the automatic building of the treasure map as they provide their answers.

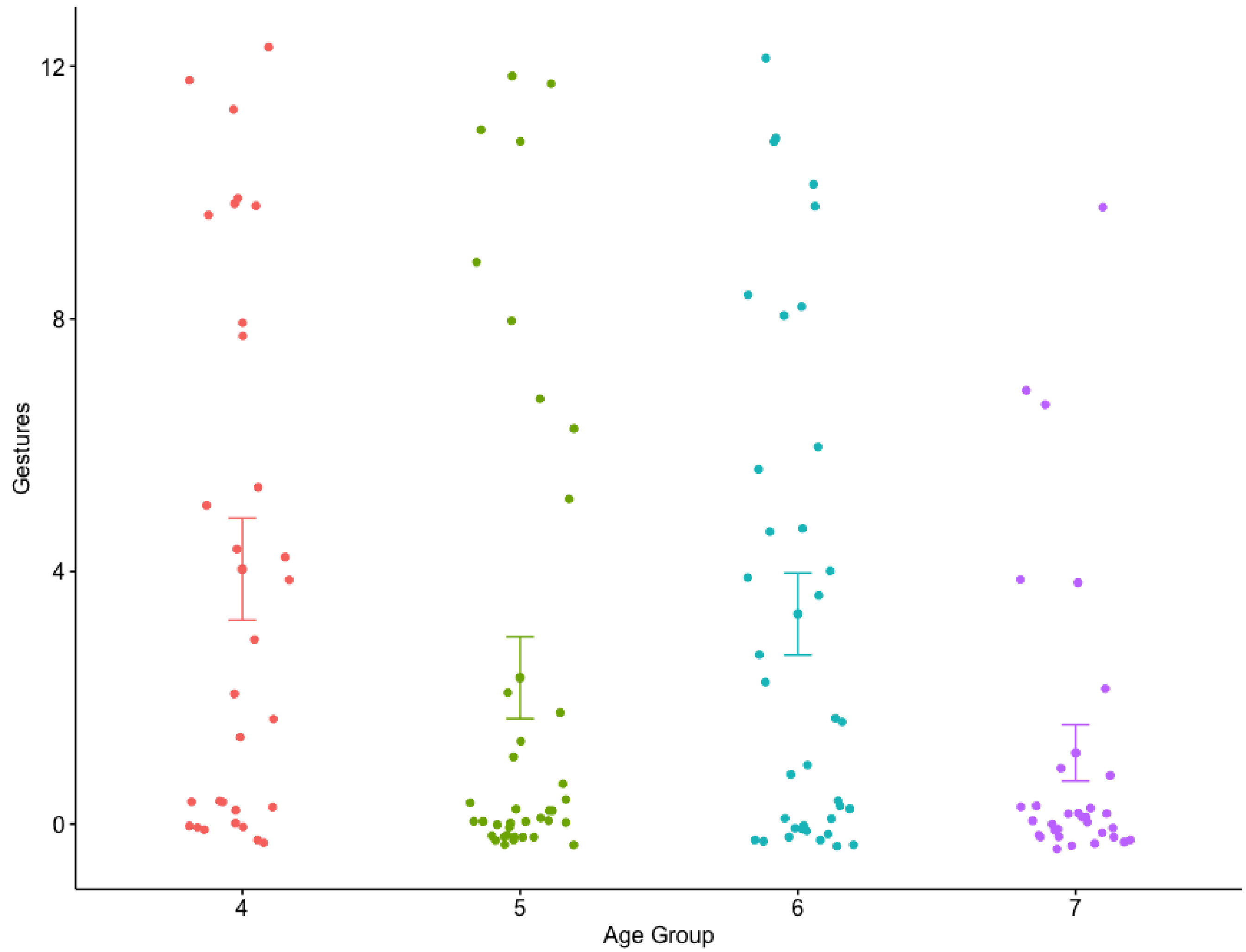


Figure 8. Use of gestures by age group. Bars represent standard error.

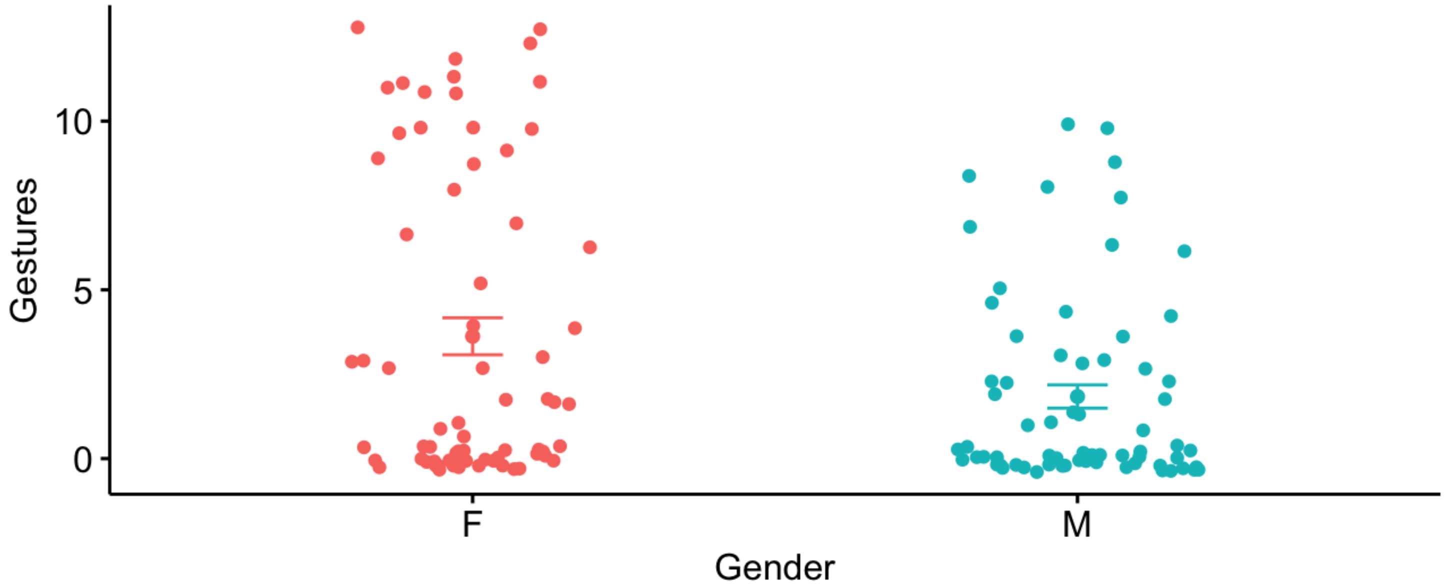


Figure 9. Use of gestures by Gender. Bars represent standard error

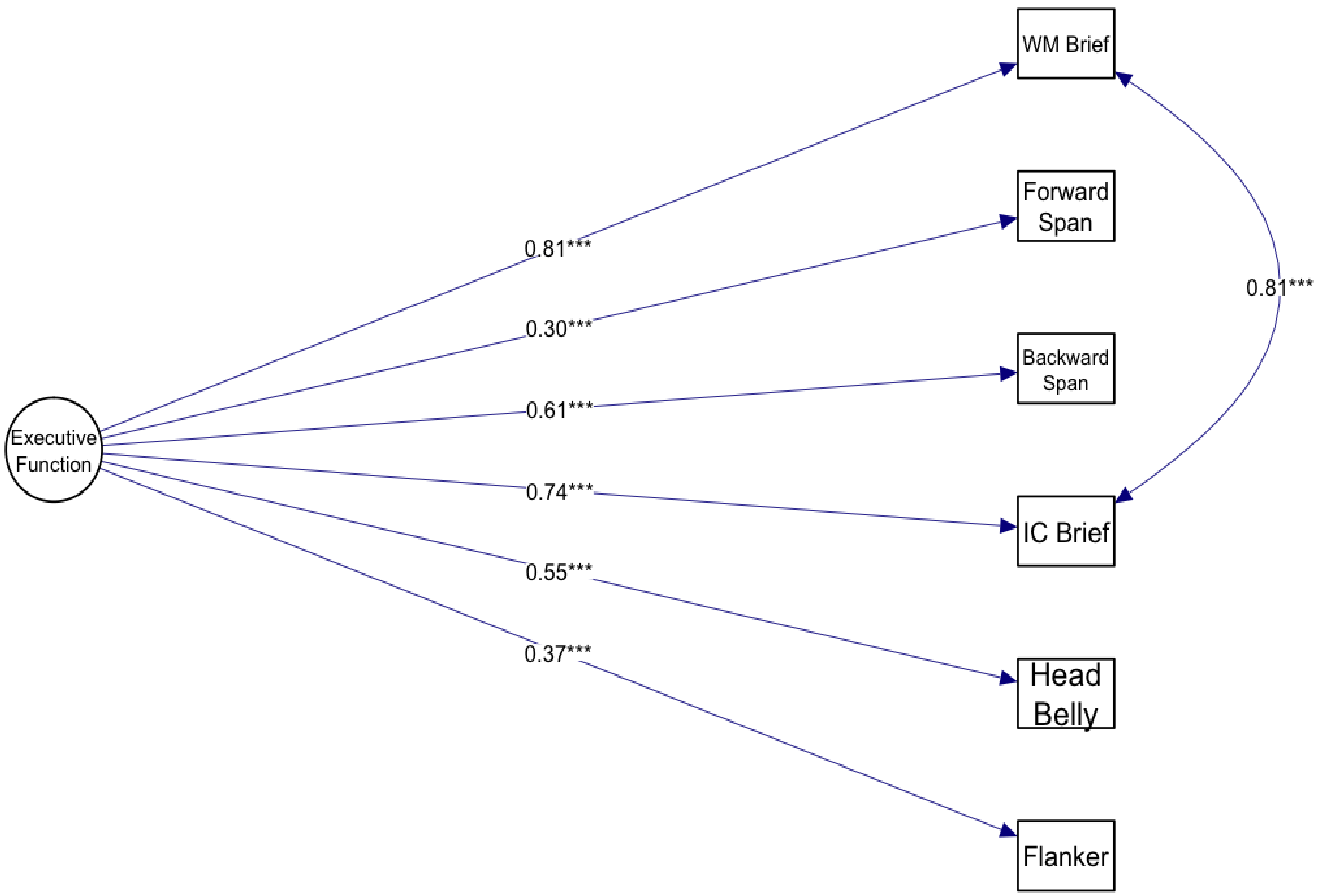


Figure 10. Model 1 - Confirmatory factor analysis displaying standardized loadings. Additional covariances not pictured for ease of interpretation; cov(executive function, age) = 0.938, $p < 0.001$

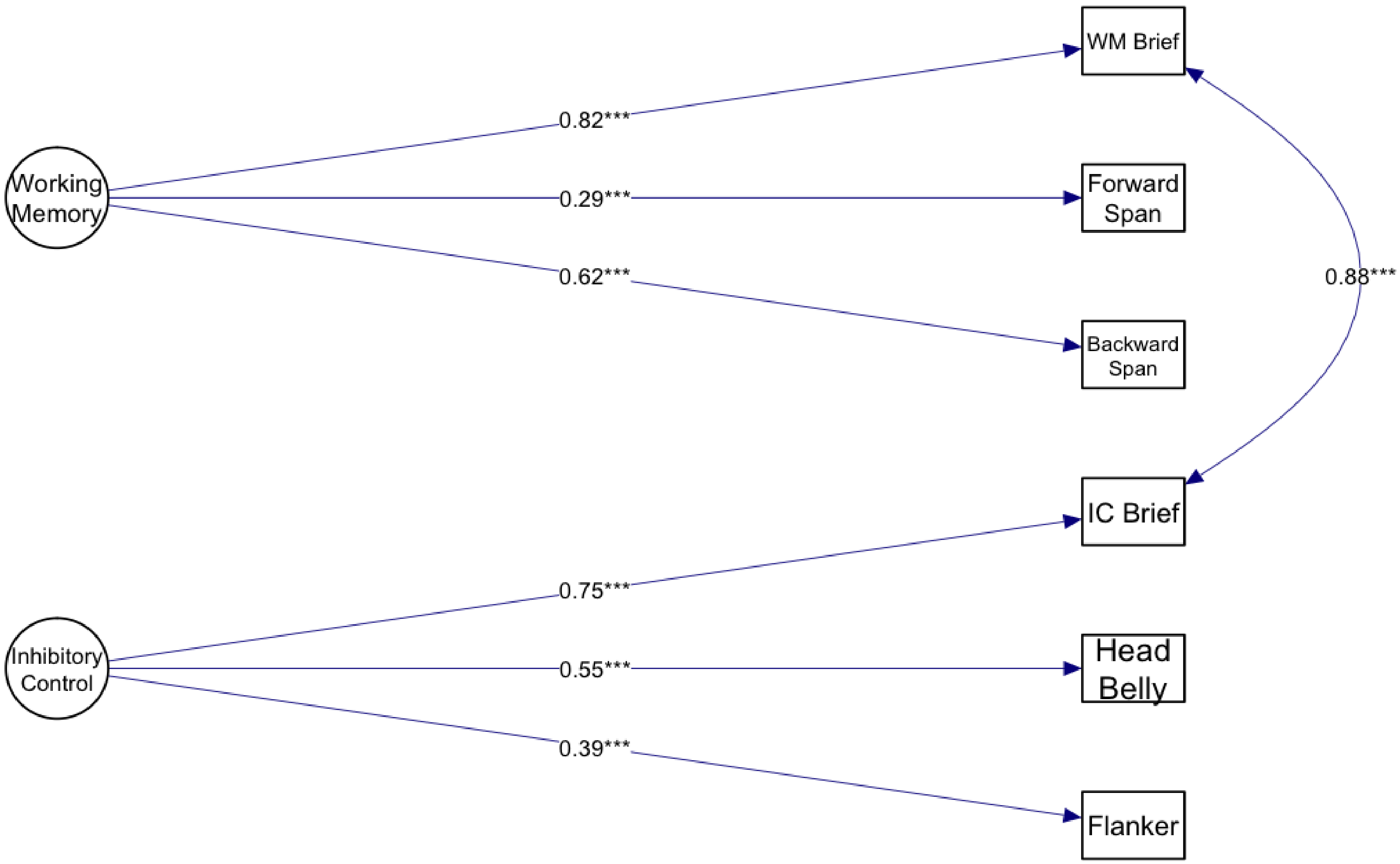


Figure 11. Model 2: Confirmatory factor analysis displaying standardized loadings and correlations. Additional covariances not pictured for ease of interpretation; cov(working memory, age) = 0.928, $p < 0.001$, cov(inhibitory control, age) = 0.926, $p < 0.001$, cov(working memory, inhibitory control) = 0.951, $p < 0.001$

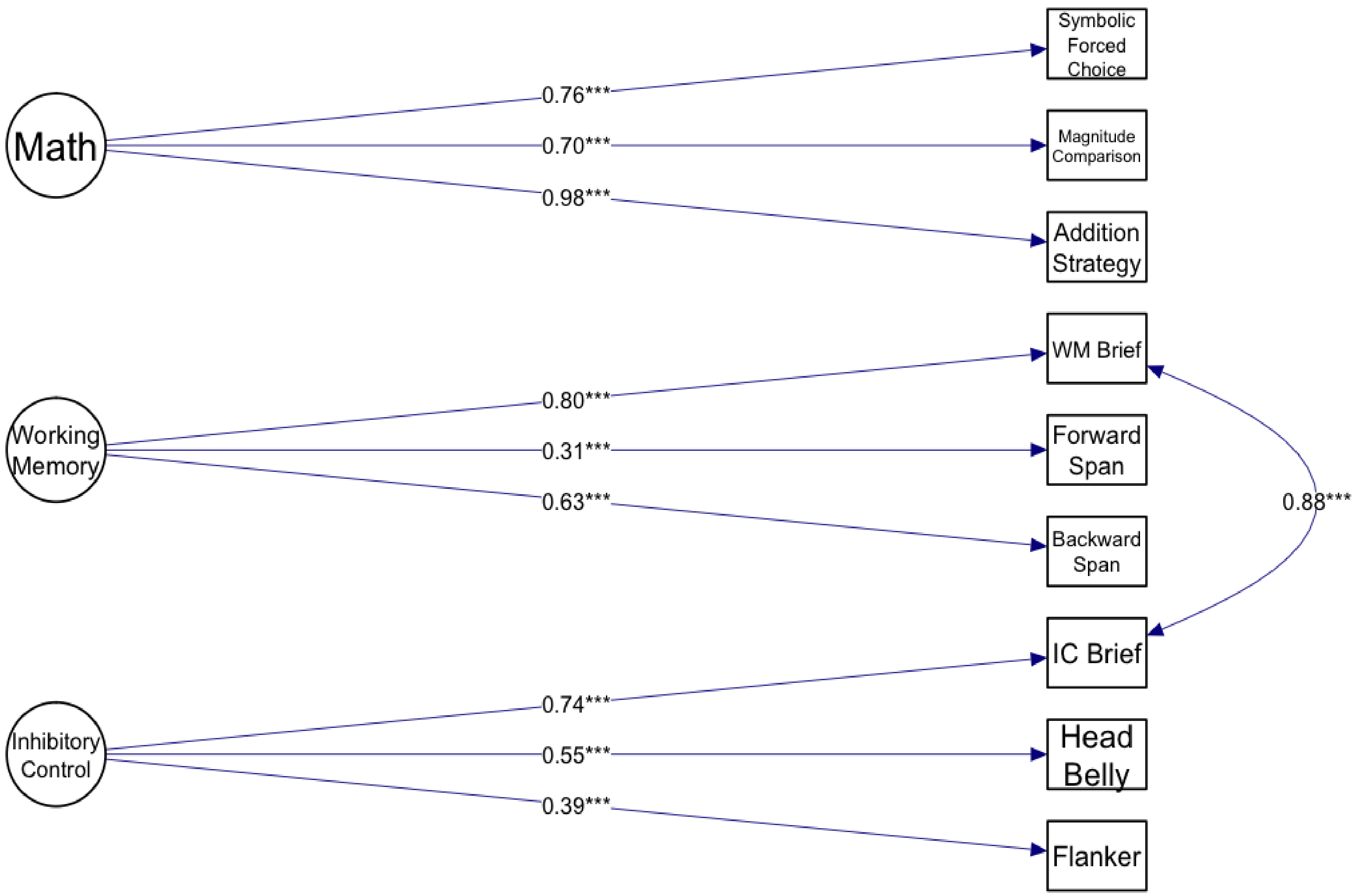


Figure 12. Model 3 - Confirmatory factor analysis displaying standardized loadings and correlations. Additional covariances not pictured for ease of interpretation; cov(working memory, age) = 0.929, p< 0.001, cov(inhibitory control, age) = 0.924, p< 0.001, cov(math, age) = 0.709, p< 0.001, cov(working memory, inhibitory control) = 0.953, p< 0.001, cov(math, inhibitory control) = 0.712, p< 0.001, cov(math, working memory) = 0.743, p< 0.001

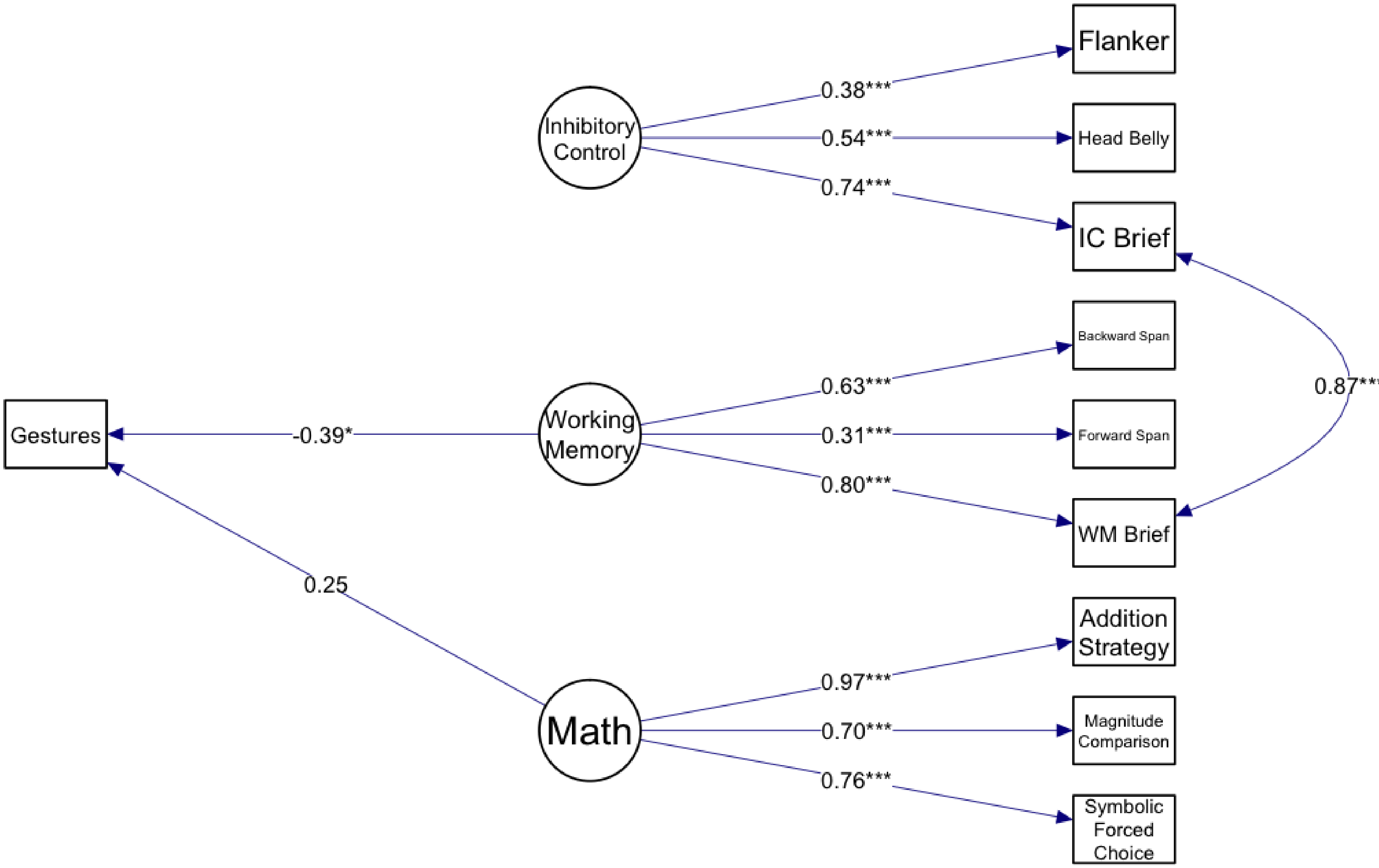


Figure 13. Model 4 - Results from the structural model predicting gesture, displaying standardized loadings and correlations, *p<0.05. Additional covariances not pictured for ease of interpretation; cov(working memory, age) = 0.937, p< 0.001, cov(inhibitory control, age) = 0.933, p< 0.001, cov(math, age) = 0.710, p< 0.001, cov(working memory, inhibitory control) = 0.956, p< 0.001, cov(math, inhibitory control) = 0.717, p< 0.001, cov(math, working memory) = 0.749, p< 0.001, cov(gestures, gender) = 0.249, p= 0.002

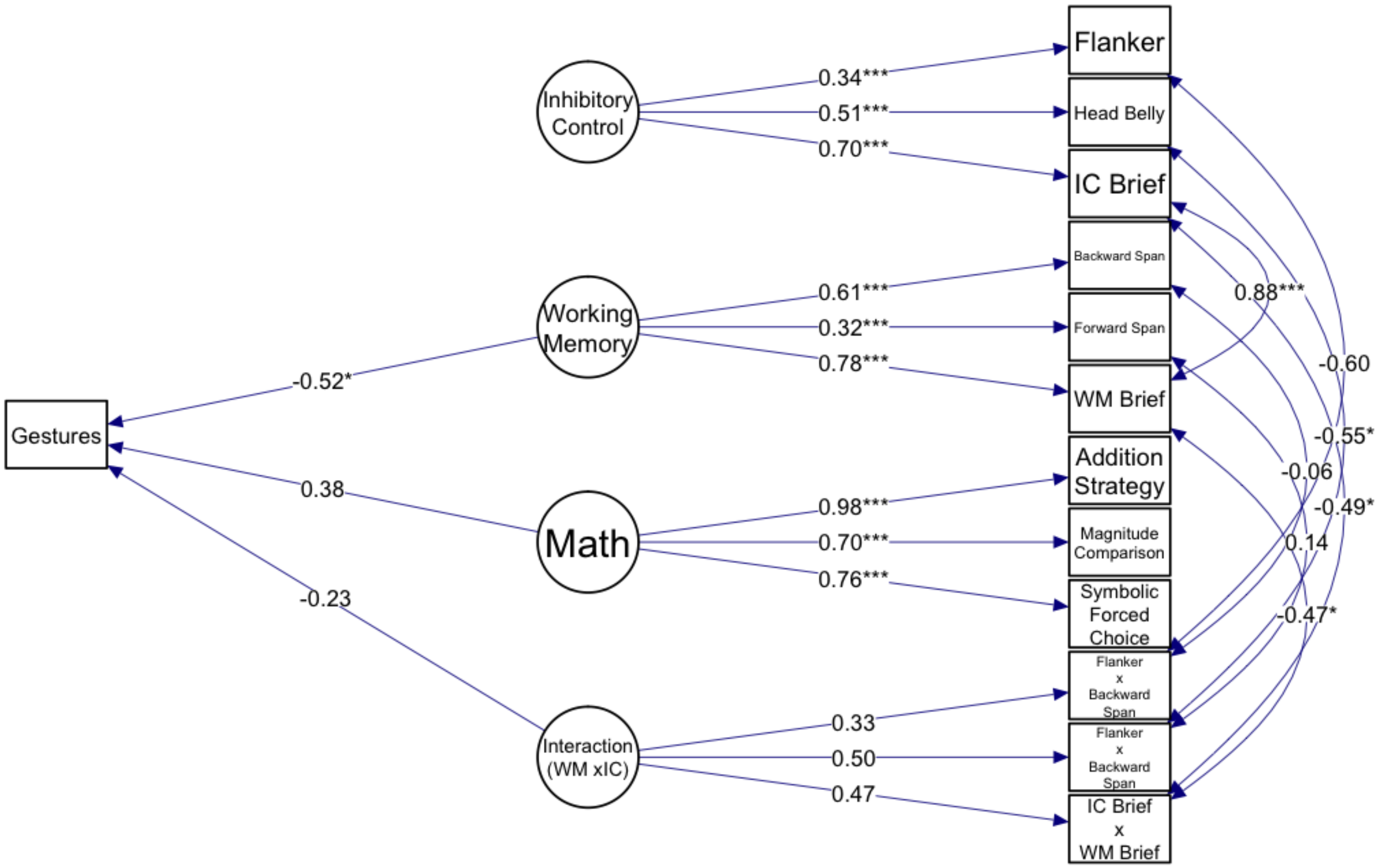


Figure 14. Model 5 - Results from the structural model predicting gesture with an added interaction term, displaying standardized loadings and correlations, **p*<0.05. Additional covariances are not pictured for ease of interpretation; cov(working memory, age) = 0.949, $p < 0.001$, cov(inhibitory control, age) = 0.945, $p < 0.001$, cov(math, age) = 0.687, $p < 0.001$, cov(working memory, inhibitory control) = 0.960, $p < 0.001$, cov(math, inhibitory control) = 0.696, $p < 0.001$, cov(math, working memory) = 0.728, $p < 0.001$, cov(gestures, inhibitory control) = 0.005, $p = 0.905$, cov(gestures, math) = 0.120, $p = 0.110$, cov(gestures, gender) = 0.244, $p = 0.002$

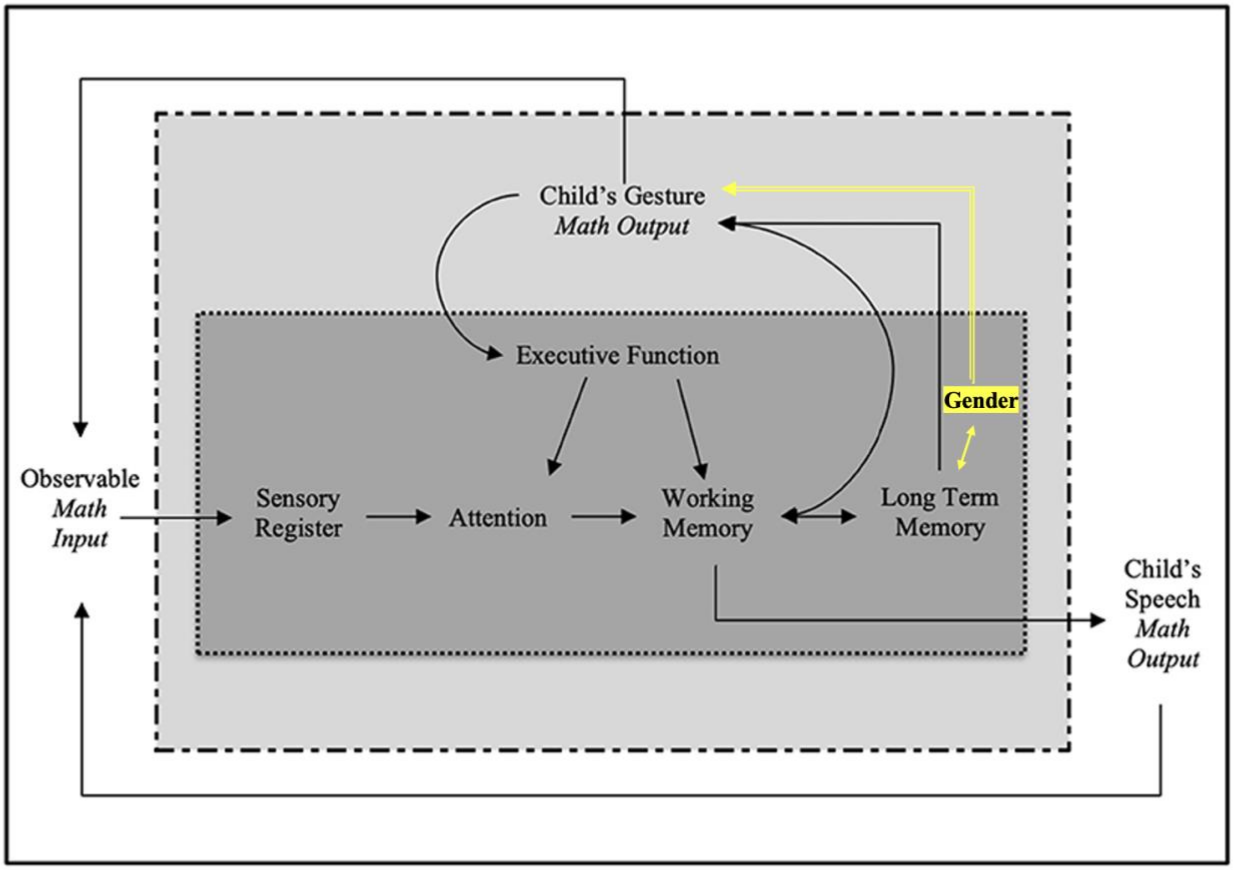


Figure 15. The final proposed model including domain general, domain specific, and socioemotional factors.

Appendices

Appendix A: Sample Task Scripts and Survey Questions

Session 1 Scripts

Note: all scripts are dependent on selections children make in the gorilla portal, and thus are not automatically played in this order. However, children may hear a set or all the following recorded audio portions when participating in these games.

<u>Flanker Task – Fish Game Script</u>

Welcome, today we are going to play a game with fish

This fish is swimming Right

This fish is swimming Left

In this game you should only watch the middle fish, the one in the center of your screen

Press the space bar to continue

To play this game, place your fingers on the A and L keys on your keyboard

Your fingers should look like this

Setup & game components plays based on what the child presses

Let's practice pressing L

Press the L Key now

Let's practice pressing A

Press the A key now

That's not quite right, let's try again.

That was a bit too slow. Let's do it again and try to press the key faster this time.

In this game, the fish you are watching will be swimming with other fish

You should only pay attention to the fish in the middle

This fish is swimming Left

This fish is swimming Right

Press the A key if the fish is swimming Left

Press the L key if the fish is swimming Right

Which way is the middle fish swimming?

Press the matching key

Now it's your turn to decide which way the fish is swimming

Let’s start with some practice

Now we will start the real game

You can have a break if you want! Just press the space bar when you feel ready to continue.

We have finished this activity. Congratulations

Magnitude Comparison - Magician's Spell Book

In this game, you're going to help a wizard cast their spells! In order to cast a spell, you should look at the spell book and decide which page has the bigger number.

Press the "a" key if the bigger number is on the left side, press the "l" key if the bigger number is on the right side!

Let's start with a practice

Which number is bigger?

Press the key for the bigger side now!

If too slow: Oops, that was a bit too slow! Let's try again.

If wrong in practice: That's not quite right. Press the key for the bigger number.

If correct in practice: That's right! Good job! Let's play the real game. In the real game, you won't know if your spell worked right away. Keep choosing the bigger number until the end of the game to find out if your spell worked! Good luck!

Awesome job! You cast the spells!

Forced Choice Arithmetic – Cookie Game

Welcome to the cookie game! In this game, you will see math cookie problems that two other children solved! For each problem, you will see one child's answers to the math problem left, and one on the right. It's your job to figure out which child solved the problem correctly.

Let's start with a practice

Finley says that 1 plus 1 equals 1 and Jamie says that 1 plus 1 equals 2.

You will press "a" if you think Finley solved it correctly

You will press "l" if you think Jamie solved it correctly

Who do you think solved the problem correctly? Press either the a or l key now

Let's play the real game now

Finley says 1 plus 2 equals 3

Jamie says 1 plus 2 equals 1.

Who do you think solved the problem correctly? Press either the a or l key now

Avery says 6 plus 3 equals 9

Jamie says 6 plus 3 equals 10

Who do you think solved the problem correctly? Press either the a or l key now

Finley says 2 plus 2 equals 1

Avery says 2 plus 2 equals 4

Who do you think solved the problem correctly? Press either the a or l key now

Jamie says 3 plus 5 equals 8

Avery says 3 plus 5 equals 4

Who do you think solved the problem correctly? Press either the a or l key now

Jamie says 7 plus 4 equals 12

Finley says 7 plus 4 equals 11

Who do you think solved the problem correctly? Press either the a or l key now

Great job! You finished the cookie game.

Session 2 Scripts

<u>Math Adventures Game</u>

"This game is called Math Adventures. We're going to work together to get pieces of a treasure map to find the treasure. To get a new piece of the map, I'm going to show you some number problems. I want you to solve each problem as quickly as you can, without making too many mistakes! You can use whatever way is easiest for you to get the answer. Once you solve the problem, you'll start collecting pieces of the map to find the treasure!"

> *(Except paper and pencil)*

"Alright! First, we're going to do an example problem together"

> *(Click to the next slide - if you think their screen might be frozen/if they had issues with the blue screen, ask them if their screen is yellow now)*

"What is 2 + 2?"

> Correct response: "That's right!"
>
> Incorrect response: "Actually, 2+2 is 4."

"How did you get that answer?"

**If they don't respond or understand, then say "How did you solve the problem?" or "How did you find the answer was X?" **If child says, "I don't know." or gives an outrageous number encourage them to guess, "Just tell me your best guess" or "I want you think really hard for this one.

> *(Click to the next slide that shows the first puzzle piece)*

"Alright! Here's your first puzzle piece. Let's keep going"

> *(Repeat the prompts "What is ____" and "How did you get that answer?" for every math problem. If you have internet connectivity issues, check in once every few questions by saying things like "What do you see in the new puzzle piece? Do you see the sharks?)*

Do NOT give the child the correct answer, say "good job" or any indication of whether it is right or wrong.

Forward Span - Color Game

This is the color game

In this game, you will hear me say some color words out loud.

Do your best to remember as many colors in the same order that you hear them.

Then, repeat the list of color words out loud, in the same order that I said them

It's very important that you listen carefully.

You will only hear the list of color words one time before it is your turn to say.

Let's start with a practice

Green Blue

Did you say, "Green Blue?"

If so, that's right! Because those are the same color words in the same order I said them.

Let's try another practice.

Listen carefully, you'll only hear the colors one time

Pink Gold

Did you say "Pink Gold?" If so, that's right! Because those are the same color words in the same order I said them.

Now let's play the real game.

Remember you will only hear each list one time, so listen carefully!

white, green

brown, red

blue, pink, gold

black, red, brown

grey, white, green, pink

blue, gold, green, black

white, grey, brown, gold, pink

green, blue, black, grey, brown

pink, gold, grey, black, red, white

brown, gold, green, red, blue, black

red, grey, gold, green, white, pink, blue

gold, pink, green, blue, white, red, brown

Great job! Let's play the last game.

Backward Span – Animal Game

Now let's play the animal game. In this game, you will hear me say a list of animals out loud. Then, you should repeat the list of animals in reverse/backwards order from how I said them. So, you will say the last animal that I said FIRST, and the first animal I said LAST. Do your best to remember as many animals in reverse order that you can. Do not write them down. It's very important that you listen carefully. You will only hear the list of animals one time before it is your turn to say them in reverse order

Let's start with a practice

Cow Deer

Did you say "Deer, Cow?"

If so, that's right! Because those are the same animals that I said, in the reverse order from how I said them. Let's try another practice

Bird Duck

Did you say "Duck, Bird?"

If so, that's right! Because those are the same animals that I said, in the reverse order from how I said them. Now let's play the real game. Remember you will only hear each list one time, so listen carefully!

cat, horse

pig, duck

fox, horse, dog

rat, pig, sheep

bird, cat, bear, dog

duck, cow, goat, rat

mouse, horse, bear, deer, cow

dog, bird, duck, frog, wolf

whale, deer, goat, frog, cat, pig

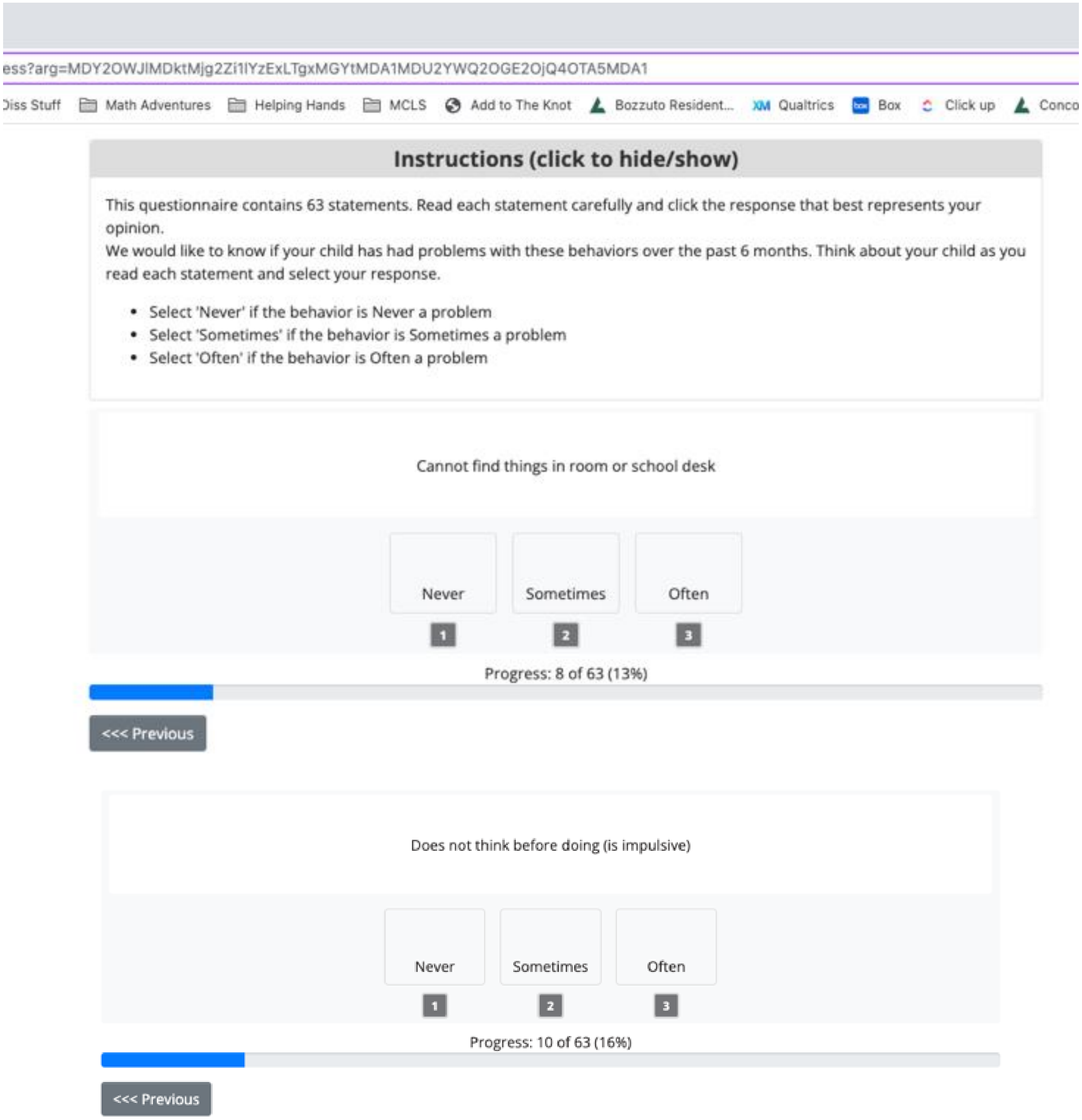
goat, bear, dog, horse, sheep, rat

wolf, bear, rat, bird, dog, duck, fox

horse, cat, goat, mouse, pig, frog, whale

Great job!

Parent BRIEF Example Questions



ess?arg=MDY2OWJlMDktMjg2Zi1lYzExLTgxMGYtMDA1MDU2YWQ2OGE2OjQ4OTA5MDA1

Diss Stuff | Math Adventures | Helping Hands | MCLS | Add to The Knot | Bozzuto Resident... | Qualtrics | Box | Click up | Conco

Instructions (click to hide/show)

This questionnaire contains 63 statements. Read each statement carefully and click the response that best represents your opinion.
We would like to know if your child has had problems with these behaviors over the past 6 months. Think about your child as you read each statement and select your response.

- Select 'Never' if the behavior is Never a problem
- Select 'Sometimes' if the behavior is Sometimes a problem
- Select 'Often' if the behavior is Often a problem

Cannot find things in room or school desk

Never 1 | Sometimes 2 | Often 3

Progress: 8 of 63 (13%)

<<< Previous

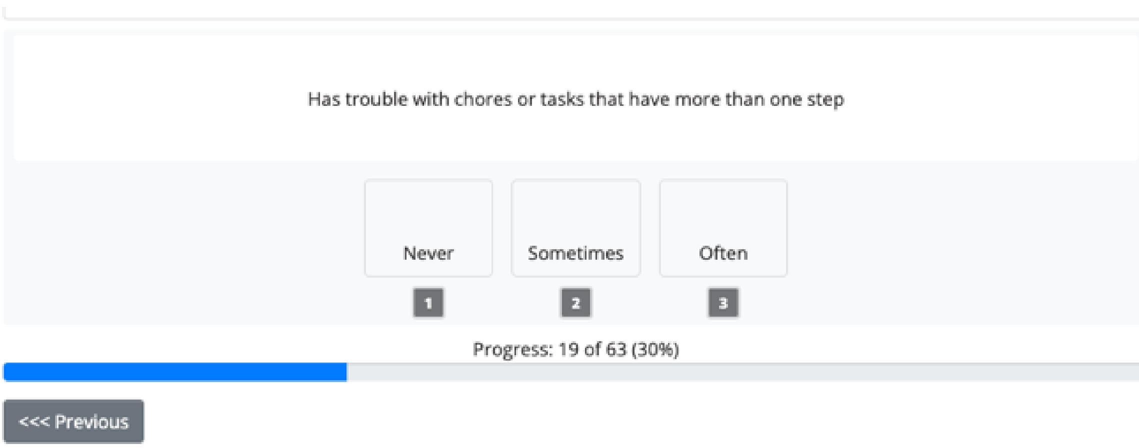
Does not think before doing (is impulsive)

Never 1 | Sometimes 2 | Often 3

Progress: 10 of 63 (16%)

<<< Previous


Has a short attention span
Never
Sometimes
Often
1
2
3
Progress: 12 of 63 (19%)
<<< Previous


Has trouble with chores or tasks that have more than one step
Never
Sometimes
Often
1
2
3
Progress: 19 of 63 (30%)
<<< Previous

Parent Demographic Survey

Default Question Block

Please enter the ***unique identifier number*** provided to you via email

Child's Race

(Check the one that best describes your child)

- African-American or Black
- Caucasian/White
- Asian or Pacific Islander
- American Indian or Alaska Native
- Biracial/Mixed Race
- Other

Is your child Hispanic or Latino?

- Yes
- No

How many people typically reside in your household?

What is your yearly household income?

- Less than $20,000
- $20,000 to $34,999
- $35,000 to $49,999
- $50,000 to $74,999
- $75,000 to $99,999
- Over $100,000

Is there another caregiver/parent in your family, besides yourself (e.g. mother, father, grandparent)?

- ○ Yes
- ○ No

Please indicate the other caregiver/parent's relationship to the child

- ○ Mother
- ○ Father
- ○ Grandma
- ○ Grandpa
- ○ Other ________

What is caregiver/parent 2's highest level of education?

- ○ Less than High School
- ○ Some High School Coursework
- ○ High School Diploma/GED
- ○ Some College Coursework/ Vocational Training
- ○ 2-year College Degree (Associates)
- ○ 4-year College Degree (BA/BS)
- ○ Postgraduate or Professional degree (MA, PhD, MD, JD)

Please indicate your relationship to the child (e.g. mother, father, grandparent, etc.)

- ○ Mother
- ○ Father
- ○ Grandma
- ○ Grandpa
- ○ Other ____________

What is your highest level of education?

- ○ Less than High School
- ○ Some High School Coursework
- ○ High School Diploma/GED
- ○ Some College Coursework/ Vocational Training
- ○ 2-year College Degree (Associates)
- ○ 4-year College Degree (BA/BS)
- ○ Postgraduate or Professional degree (MA, PhD, MD, JD)

Is there another caregiver/parent in your family, besides yourself (e.g. mother, father, grandparent)?

- ○ Yes
- ○ No

Appendix B: IRB Approval Letter

UNIVERSITY OF MARYLAND

INSTITUTIONAL REVIEW BOARD

1204 Marie Mount Hall
College Park, MD 20742-5125
TEL 301.405.4212
FAX 301.314.1475
irb@umd.edu
www.umresearch.umd.edu/IRB

DATE:	January 7, 2022
TO:	Geetha Ramani
FROM:	University of Maryland College Park (UMCP) IRB
PROJECT TITLE:	[1843961-1] Pointing Out the Relations Between Children's Math Knowledge, Executive Function Abilities, and Gestures Use During Arithmetic Problem Solving.
SUBMISSION TYPE:	New Project
ACTION:	APPROVED
APPROVAL DATE:	January 7, 2022
REVIEW TYPE:	Expedited Review
REVIEW CATEGORY:	Expedited review category #7. 45CFR46.404 applies.

Thank you for your submission of New Project materials for this project. The University of Maryland College Park (UMCP) IRB has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a project design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

Prior to final approval of this project scientific review was completed by the IRB Member reviewer.

This submission has received Expedited Review based on the applicable federal regulations.

This project has been determined to be a MINIMAL RISK project.

Please remember that informed consent is a process beginning with a description of the project and insurance of participant understanding followed by a signed consent form. Informed consent must continue throughout the project via a dialogue between the researcher and research participant. Unless a consent waiver or alteration has been approved, Federal regulations require that each participant receives a copy of the consent document.

Please note that any revision to previously approved materials must be approved by this committee prior to initiation. Please use the appropriate Amendment forms for this procedure.

All UNANTICIPATED PROBLEMS involving risks to subjects or others (UPIRSOs) and SERIOUS and UNEXPECTED adverse events must be reported promptly to this office. Please use the appropriate reporting forms for this procedure. All FDA and sponsor reporting requirements should also be followed. All NON-COMPLIANCE issues or COMPLAINTS regarding this project must be reported promptly to this office.

Please note that all research records must be retained for a minimum of seven years after the completion of the project.

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.

References

Agostino, A., Johnson, J., & Pascual-Leone, J. (2010). Executive functions underlying multiplicative reasoning: Problem type matters. *Journal of Experimental Child Psychology*, *105*(4), 286–305. https://doi.org/10.1016/j.jecp.2009.09.006

Aldugom, M., Fenn, K., Day, A., & Cook, S. W. (2021). The role of verbal and visuospatial working memory in supporting mathematics learning with and without hand gesture. In *Proceedings of the Annual Meeting of the Cognitive Science Society* (Vol. 43, No. 43).

Alibali, M. W., & DiRusso, A. A. (1999). The function of gesture in learning to count: More than keeping track. *Cognitive Development*, *14*(1), 37–56. https://doi.org/10.1016/S0885-2014(99)80017-3

Alibali, M. W., Flevares, L. M., & Goldin-Meadow, S. (1997). Assessing knowledge conveyed in gesture: Do teachers have the upper hand? *Journal of Educational Psychology*, 89(1), 183–193. https://doi.org/10.1037/0022-0663.89.1.183

Alibali, M. W., & Goldin-Meadow, S. (1993). Gesture-speech mismatch and mechanisms of learning: What the hands reveal about a child′s state of mind. *Cognitive Psychology*, *25*(4), 468–523. https://doi.org/10.1006/cogp.1993.1012

Alibali, M. W., Heath, D. C., & Myers, H. J. (2001). Effects of visibility between speaker and listener on gesture production: Some gestures are meant to be seen. *Journal of Memory and Language*, *44*(2), 169–188. https://doi.org/10.1006/jmla.2000.2752

Alibali, M. W., & Kita, S. (2010). Gesture highlights perceptually present information for speakers. *Gesture*, *10*(1), 3–28. https://doi.org/10.1075/gest.10.1.02ali

Alibali, M. W., & Nathan, M. J. (2012). Embodiment in mathematics teaching and learning: Evidence from learners' and teachers' gestures. *Journal of the Learning Sciences*, 21(2), 247–286. https://doi.org/10.1080/10508406.2011.611446

Allison, P. D. (1999). *Multiple Regression: A Primer* (1st edition). Pine Forge Press.

Alloway, T. P., & Alloway, R. G. (2010). Investigating the predictive roles of working memory and IQ in academic attainment. *Journal of Experimental Child Psychology*, 106(1), 20–29. https://doi.org/10.1016/j.jecp.2009.11.003

Andersson, U. (2007). The contribution of working memory to children's mathematical word problem solving. *Applied Cognitive Psychology*, *21*(9), 1201–1216. https://doi.org/10.1002/acp.1317

Andersson, Ulf. (2008). Working memory as a predictor of written arithmetical skills in children: The importance of central executive functions. *British Journal of Educational Psychology*, 78(2), 181–203. https://doi.org/10.1348/000709907X209854

Anwyl-Irvine, A. L., Massonnié, J., Flitton, A., Kirkham, N., & Evershed, J. K. (2020). Gorilla in our midst: An online behavioral experiment builder. *Behavior Research Methods*, *52*(1), 388–407. https://doi.org/10.3758/s13428-019-01237-x

Ashcraft, M. H. (1982). The development of mental arithmetic: A chronometric approach. *Developmental Review*, *2*(3), 213–236. https://doi.org/10.1016/0273-2297(82)90012-0

Ashcraft, M. H., & Kirk, E. P. (2001). The relationships among working memory, math anxiety, and performance. *Journal of experimental psychology: General*, 130(2), 224.

Baker, S. T., Gjersoe, N. L., Sibielska-Woch, K., Leslie, A. M., & Hood, B. M. (2011). Inhibitory control interacts with core knowledge in toddlers' manual search for an occluded object. *Developmental Science*, 14(2), 270–279. https://doi.org/10.1111/j.1467-7687.2010.00972.x

Ballard, D. H., Hayhoe, M. M., Pook, P. K., & Rao, R. P. N. (1997). Deictic codes for the embodiment of cognition. *Behavioral and Brain Sciences*, 20(4), 723–742. https://doi.org/10.1017/S0140525X97001611

Barkin, R., & Ramani, G. B. (*Under Review*). Doing math by hand: Investigating the relations between children's working memory and gesture strategies during arithmetic problem solving.

Barsalou, L. W. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences*, *22*(4), 577–660. https://doi.org/10.1017/S0140525X99002149

Barrouillet, P., & Lépine, R. (2005). Working memory and children's use of retrieval to solve addition problems. *Journal of Experimental Child Psychology*, *91*(3), 183–204. https://doi.org/10.1016/j.jecp.2005.03.002

Bisanz, J., Morrison, F. J., & Dunn, M. (1995). Effects of age and schooling on the acquisition of elementary quantitative skills. Developmental Psychology, 31(2), 221–236.

Blair, C., & Razza, R. P. (2007). Relating effortful control, executive function, and false belief understanding to emerging math and literacy ability in kindergarten. *Child Development*, *78*(2), 647–663. https://doi.org/10.1111/j.1467-8624.2007.01019.x

Borst, G., Poirel, N., Pineau, A., Cassotti, M., & Houdé, O. (2012). Inhibitory control efficiency in a Piaget-like class-inclusion task in school-age children and adults: A developmental negative priming study. *Developmental Psychology*, *49*. https://doi.org/10.1037/a0029622

Broaders, S. C., Cook, S. W., Mitchell, Z., & Goldin-Meadow, S. (2007). Making children gesture brings out implicit knowledge and leads to learning. *Journal of Experimental Psychology: General*, *136*(4), 539–550. https://doi.org/10.1037/0096-3445.136.4.539

Brock, L. L., Rimm-Kaufman, S. E., Nathanson, L., & Grimm, K. J. (2009). The contributions of 'hot' and 'cool' executive function to children's academic achievement, learning-related behaviors, and engagement in kindergarten. *Early Childhood Research Quarterly*, *24*(3), 337–349. https://doi.org/10.1016/j.ecresq.2009.06.001

Brookman-Byrne, A., Mareschal, D., Tolmie, A. K., & Dumontheil, I. (2018). Inhibitory control and counterintuitive science and maths reasoning in adolescence. *PLOS ONE*, 13(6), e0198973. https://doi.org/10.1371/journal.pone.0198973

Bull, R., & Espy, K. A. (2006). Working memory, executive functioning, and children's mathematics. In *Working Memory and Education* (pp. 93–123). Elsevier. https://doi.org/10.1016/B978-012554465-8/50006-5

Bull, R., Espy, K. A., Wiebe, S. A., Sheffield, T. D., & Nelson, J. M. (2011). Using confirmatory factor analysis to understand executive control in preschool children: Sources of variation in emergent mathematic achievement: Executive control and emergent mathematics. *Developmental Science*, *14*(4), 679–692. https://doi.org/10.1111/j.1467-7687.2010.01012.x

Bull, R., Johnston, R., & Roy, J. (1999). Exploring the roles of the visual-spatial sketchpad and central executive in children's arithmetical skills: Views from cognition and developmental neuropsychology. *Developmental Neuropsychology*, *15*, 421–442. https://doi.org/10.1080/87565649909540759

Bull, R., & Lee, K. (2014). Executive functioning and mathematics achievement. *Child Development Perspectives*, *8*(1), 36–41. https://doi.org/10.1111/cdep.12059

Bull, R., & Scerif, G. (2001). Executive functioning as a predictor of children's mathematics ability: Inhibition, switching, and working memory. *Developmental Neuropsychology*, *19*(3), 273–293. https://doi.org/10.1207/S15326942DN1903_3

Carey, S. (2009). Where our number concepts come from. *The Journal of Philosophy*, *106*(4), 220–254.

Carpenter, T. P., & Moser, J. M. (1984). The acquisition of addition and subtraction concepts in grades one through three. *Journal for Research in Mathematics Education*, *15*(3), 179–202. https://doi.org/10.2307/748348

Caviola, S., Mammarella, I. C., Cornoldi, C., & Lucangeli, D. (2012). The involvement of working memory in children's exact and approximate mental addition. *Journal of Experimental Child Psychology*, 112(2), 141–160. https://doi.org/10.1016/j.jecp.2012.02.005

Clark, C. A. C., Pritchard, V. E., & Woodward, L. J. (2010). Preschool executive functioning abilities predict early mathematics achievement. *Developmental Psychology*, *46*(5), 1176–1191. https://doi.org/10.1037/a0019672

Clark, C. A. C., Sheffield, T. D., Wiebe, S. A., & Espy, K. A. (2013). Longitudinal associations between executive control and developing mathematical competence in preschool boys and girls. *Child Development*, 84(2), 662–677. https://doi.org/10.1111/j.1467-8624.2012.01854.x

Clark, R. (1999). Yin and yang cognitive motivational processes operating in multimedia learning environments. *Cognition and Multimedia Design*. Herleen, Netherlands: Open University Press.

Chu, M., Meyer, A., Foulkes, L., & Kita, S. (2014). Individual differences in frequency and saliency of speech-accompanying gestures: The role of cognitive abilities and empathy. *Journal of Experimental Psychology: General*, *143*(2), 694–709. https://doi.org/10.1037/a0033861

Christ, S. E., White, D. A., Mandernach, T., & Keys, B. A. (2001). Inhibitory control across the life span. *Developmental neuropsychology*, 20(3), 653-669.

Christian, K., Bachman, H. J., & Morrison, F. J. (2001). Schooling and cognitive development. In Environmental effects on cognitive abilities (pp. 287–335). Mahwah, NJ: Lawrence Erlbaum Associates.

Church, R. B. (1999). Using gesture and speech to capture transitions in learning. *Cognitive Development*, *14*(2), 313–342. https://doi.org/10.1016/S0885-2014(99)00007-6

Church, R., B. & Goldin-Meadow, S. (1986). The mismatch between gesture and speech as an index of transitional knowledge. *Cognition*, *23*(1), 43–71. https://doi.org/10.1016/0010-0277(86)90053-3

Church, R. B., Kelly, S. D., & Lynch, K. (2000). Immediate memory for mismatched speech and representational gesture across development. *Journal of Nonverbal Behavior*, *24*(2), 151–174. https://doi.org/10.1023/A:1006610013873

Church, R. B., Ayman-Nolley, S., & Mahootian, S. (2004). The role of gesture in bilingual education: Does gesture enhance learning? *International Journal of Bilingual Education and Bilingualism*, *7*(4), 303–319. https://doi.org/10.1080/13670050408667815

Claesens, A., & Engel, M. (2013). How important is where you start? Early mathematics knowledge and later school success. *Teachers College Record*, *115*(6), 1–29.

Clements, D. H., Sarama, J., & Germeroth, C. (2016). Learning executive function and early mathematics: Directions of causal relations. *Early Childhood Research Quarterly*, *36*, 79–90. https://doi.org/10.1016/j.ecresq.2015.12.009

Congdon, E. L., Novack, M. A., Brooks, N., Hemani-Lopez, N., O'Keefe, L., & Goldin-Meadow, S. (2017). Better together: Simultaneous presentation of speech and gesture in math instruction supports generalization and retention. *Learning and Instruction*, *50*, 65–74. https://doi.org/10.1016/j.learninstruc.2017.03.005

Congdon, E. L., Kwon, M.-K., & Levine, S. C. (2018). Learning to measure through action and gesture: Children's prior knowledge matters. *Cognition*, *180*, 182–190. https://doi.org/10.1016/j.cognition.2018.07.002

Cook, S. W., Duffy, R. G., & Fenn, K. M. (2013). Consolidation and transfer of learning after observing hand gesture. *Child Development*, *84*(6), 1863–1871. https://doi.org/10.1111/cdev.12097

Cook, S. W., Friedman, H. S., Duggan, K. A., Cui, J., & Popescu, V. (2017). Hand gesture and mathematics learning: lessons from an avatar. *Cognitive Science*, *41*(2), 518–535. https://doi.org/10.1111/cogs.12344

Cook, S. W., Mitchell, Z., & Goldin-Meadow, S. (2008). Gesturing makes learning last. *Cognition*, *106*(2), 1047–1058. https://doi.org/10.1016/j.cognition.2007.04.010

Cook, S. W., Yip, T. K., & Goldin-Meadow, S. (2012). Gestures, but not meaningless movements, lighten working memory load when explaining math. *Language and Cognitive Processes*, *27*(4), 594–610. https://doi.org/10.1080/01690965.2011.567074

Coulanges, L., Abreu-Mendoza, R. A., Varma, S., Uncapher, M. R., Gazzaley, A., Anguera, J., & Rosenberg-Lee, M. (2021). Linking inhibitory control to math achievement via comparison of conflicting decimal numbers. *Cognition*, *214*, 104767. https://doi.org/10.1016/j.cognition.2021.104767

Cowan, N., Saults, J. S., & Elliot, E. M. (2002). The search for what is fundamental in the development of working memory. *Advances in child development and behavior, Vol. 29* (pp. 1–49). Academic Press. https://doi.org/10.1016/S0065-2407(02)80050-7

Cragg, L., & Gilmore, C. (2014). Skills underlying mathematics: The role of executive function in the development of mathematics proficiency. *Trends in Neuroscience and Education*, *3*(2), 63–68. https://doi.org/10.1016/j.tine.2013.12.001

Cragg, L., Keeble, S., Richardson, S., Roome, H. E., & Gilmore, C. (2017). Direct and indirect influences of executive functions on mathematics achievement. *Cognition*, 162, 12–26. https://doi.org/10.1016/j.cognition.2017.01.014

Crowder, E. M., & Newman, D. (1993). Telling what they know: The role of gesture and language in children's science explanations. *Pragmatics & Cognition*, *1*(2), 341–376. https://doi.org/10.1075/pc.1.2.06cro

Cvencek, D., Meltzoff, A. N., & Greenwald, A. G. (2011). Math–gender stereotypes in elementary school children. Child development, 82(3), 766-779.

Daubert, E. (2018). Guided discovery activities supporting mathematical understanding in children [Digital Repository at the University of Maryland]. https://doi.org/10.13016/M24M91D9N

Delgado, B., Gómez, J. C., & Sarriá, E. (2011). Pointing gestures as a cognitive tool in young children: Experimental evidence. *Journal of Experimental Child Psychology*, 110(3), 299–312. https://doi.org/10.1016/j.jecp.2011.04.010

Devine, A., Fawcett, K., Szűcs, D., & Dowker, A. (2012). Gender differences in mathematics anxiety and the relation to mathematics performance while controlling for test anxiety. *Behavioral and brain functions*, *8*(1), 1-9.

Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., Pagani, L. S., Feinstein, L., Engel, M., Brooks-Gunn, J., Sexton, H., Duckworth, K., & Japel, C. (2007). School readiness and later achievement. *Developmental Psychology*, *43*(6), 1428–1446. https://doi.org/10.1037/0012-1649.43.6.1428

Edwards, L. D. (2009). Gestures and conceptual integration in mathematical talk. *Educational studies in mathematics*, 70(2), 127-141.

Ellemers, N. (2018). Gender stereotypes. *Annual review of psychology*, *69*, 275-298.

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a non search task. *Perception & Psychophysics*, *16*(1), 143–149. https://doi.org/10.3758/BF03203267

Espy, K. A., McDiarmid, M. M., Cwik, M. F., Stalets, M. M., Hamby, A., & Senn, T. E. (2004). The Contribution of Executive Functions to Emergent Mathematic Skills in Preschool Children. *Developmental Neuropsychology*, *26*(1), 465–486. https://doi.org/10.1207/s15326942dn2601_6

Epskamp, S. (2019). semPlot: Path Diagrams and Visual Analysis of Various SEM Packages' Output. *R Package Version 1.1.2.* https://CRAN.R-project.org/package=semPlot

Fabrigar, L. R., Wegener, D. T., MacCallum, R. C., & Strahan, E. J. (1999). Evaluating the use of exploratory factor analysis in psychological research. *Psychological methods*, *4*(3), 272.

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191. https://doi.org/10.3758/BF03193146

Finney, S. J., & DiStefano, C. (2006). Non-normal and categorical data in structural equation modeling. *Structural equation modeling: A second course*, *10*(6), 269-314.

Flevares, L. M., & Perry, M. (2001). How many do you see? The use of non spoken representations in first- grade mathematics lessons. *Journal of Educational Psychology*, 93(2), 330–345. https://doi.org/10.1037/0022-0663.93.2.330.

Foundations for Success: The Final Report of the National Mathematics Advisory Panel. (2008). In *US Department of Education*. US Department of Education. https://eric.ed.gov/?id=ED500486

Friso-van den Bos, I., & van de Weijer-Bergsma, E. (2020). Classroom versus individual working memory assessment: Predicting academic achievement and the role of attention and response inhibition. *Memory*, *28*(1), 70–82. https://doi.org/10.1080/09658211.2019.1682170

Fuhs, M. W., & McNeil, N. M. (2013). ANS acuity and mathematics ability in preschoolers from low-income homes: Contributions of inhibitory control. *Developmental Science*, *16*(1), 136–148. https://doi.org/10.1111/desc.12013

Fuson, K. C. (1982). An analysis of the counting-on solution procedure in addition. In *Addition and subtraction: A cognitive perspective* (Vol. 67, p. 81). Routledge.

Garber, P., Alibali, M. W., & Goldin-Meadow, S. (1998). Knowledge conveyed in gesture is not tied to the hands. *Child Development*, *69*(1), 75. https://doi.org/10.2307/1132071

Gathercole, S. E. (1998). The development of memory. *The Journal of Child Psychology and Psychiatry and Allied Disciplines*, *39*(1), 3–27. https://doi.org/10.1017/S0021963097001753

Gathercole, S. E., Pickering, S. J., Ambridge, B., & Wearing, H. (2004). The structure of working memory from 4 to 15 Years of Age. *Developmental Psychology*, *40*(2), 177–190. https://doi.org/10.1037/0012-1649.40.2.177

Geary, D. C. (2011). Cognitive predictors of achievement growth in mathematics: A five year longitudinal study. *Developmental Psychology*, *47*(6), 1539–1552.

https://doi.org/10.1037/a0025510

Geary, D. C., Hoard, M. K., Byrd-Craven, J., & Catherine DeSoto, M. (2004). Strategy choices in simple and complex addition: Contributions of working memory and counting knowledge for children with mathematical disability. *Journal of Experimental Child Psychology*, 88(2), 121–151. https://doi.org/10.1016/j.jecp.2004.03.002

Geary, D. C., Hoard, M. K., & Hamson, C. O. (1999). Numerical and arithmetical cognition: Patterns of functions and deficits in children at risk for a mathematical disability. *Journal of Experimental Child Psychology*, *74*(3), 213–239. https://doi.org/10.1006/jecp.1999.2515

Geary, D. C., Hoard, M. K., & Nugent, L. (2012). Independent contributions of the central executive, intelligence, and in-class attentive behavior to developmental change in the strategies used to solve addition problems. *Journal of Experimental Child Psychology*, *113*(1), 49–65. https://doi.org/10.1016/j.jecp.2012.03.003

Geary, D. C., Hoard, M. K., Nugent, L., & Bailey, D. H. (2013). Adolescents' functional numeracy is predicted by their school entry number system knowledge. *PLOS ONE*, *8*(1), e54651. https://doi.org/10.1371/journal.pone.0054651

Geary, D. C., & vanMarle, K. (2016). Young children's core symbolic and nonsymbolic quantitative knowledge in the prediction of later mathematics achievement. *Developmental Psychology*, *52*(12), 2130–2144. https://doi.org/10.1037/dev0000214

Gibson, D. J., Gunderson, E. A., Spaepen, E., Levine, S. C., & Goldin-Meadow, S. (2019). Number gestures predict learning of number words. *Developmental Science*, *22*(3). https://doi.org/10.1111/desc.12791

Gillespie, M., James, A. N., Federmeier, K. D., & Watson, D. G. (2014). Verbal working memory predicts co-speech gesture: Evidence from individual differences. *Cognition*, 132(2), 174–180. https://doi.org/10.1016/j.cognition.2014.03.012

Gilmore, C., Attridge, N., Clayton, S., Cragg, L., Johnson, S., Marlow, N., Simms, V., & Inglis, M. (2013). Individual differences in inhibitory control, not non-verbal number acuity, correlate with mathematics achievement. *PLOS ONE*, *8*(6), e67374. https://doi.org/10.1371/journal.pone.0067374

Gilmore, C., Keeble, S., Richardson, S., & Cragg, L. (2015). The role of cognitive inhibition in different components of arithmetic. *ZDM*, *47*(5), 771–782. https://doi.org/10.1007/s11858-014-0659-y

Gioia, G. A., Isquith, P. K., Guy, S. C., & Kenworthy, L. *Behavior Rating Inventory of Executive Function®, Second Edition (BRIEF®2)*.

Glenberg, A. M., & Robertson, D. A. (1999). Indexical understanding of instructions. *Discourse Processes*, 28(1), 1–26. https://doi.org/10.1080/01638539909545067

Goldin-Meadow, S. (2003). Beyond words: The importance of gesture to researchers and learners. *Child Development*, *71*(1), 231–239. https://doi.org/10.1111/1467-8624.00138

Goldin-Meadow, S. (2009). How gesture promotes learning throughout childhood. *Child Development Perspectives*, *3*(2), 106–111. https://doi.org/10.1111/j.1750-8606.2009.00088.x

Goldin-Meadow, S., Alibali, M., & Church, R. (1993). Transitions in concept acquisition: Using the hand to read the mind. *Psychological Review*, *100*, 279–297. https://doi.org/10.1037//0033-295X.100.2.279

Goldin-Meadow, S., Cook, S. W., & Mitchell, Z. A. (2009). Gesturing gives children new ideas about math. *Psychological Science*, *20*(3), 267–272. https://doi.org/10.1111/j.1467-9280.2009.02297.x

Goldin-Meadow, S., Kim, S., & Singer, M. (1999). What the teacher's hands tell the student's mind about math. *Journal of Educational Psychology*, *91*(4), 720–730. https://doi.org/10.1037/0022-0663.91.4.720

Goldin-Meadow, S., Nusbaum, H. C., Garber, P., & Church, R. B. (1993). Transitions in learning: Evidence for simultaneously activated strategies. *Journal of Experimental Psychology: Human Perception and Performance*, *19*(1), 92–107. https://doi.org/10.1037/0096-1523.19.1.92

Goldin-Meadow, S., Nusbaum, H., Kelly, S. D., & Wagner, S. (2001). Explaining math: gesturing lightens the load. *Psychological Science*, *12*(6), 516–522. https://doi.org/10.1111/1467-9280.00395

Goldin-Meadow, S., Shield, A., Lenzen, D., Herzig, M., & Padden, C. (2012). The gestures ASL signers use tell us when they are ready to learn math. *Cognition*, *123*(3), 448–453. https://doi.org/10.1016/j.cognition.2012.02.006

Goldin-Meadow, S., & Wagner, S. M. (2005). How our hands help us learn. *Trends in Cognitive Sciences*, *9*(5), 234–241. https://doi.org/10.1016/j.tics.2005.03.006

Goldin-Meadow, S., Wein, D., & Chang, C. (1992). Assessing knowledge through gesture: Using children's hands to read their minds. *Cognition and Instruction*, *9*(3), 201–219. https://doi.org/10.1207/s1532690xci0903_2

Gómez, D. M., Jiménez, A., Bobadilla, R., Reyes, C., & Dartnell, P. (2015). The effect of inhibitory control on general mathematics achievement and fraction comparison in middle school children. *ZDM*, *47*(5), 801–811. https://doi.org/10.1007/s11858-015-0685-

4

Gordon, R., Chernyak, N., & Cordes, S. (2019). Get to the point: Preschoolers' spontaneous gesture use during a cardinality task. *Cognitive Development*, *52*, 100818. https://doi.org/10.1016/j.cogdev.2019.100818

Gordon, R., & Ramani, G. B. (2021). Integrating embodied cognition and information processing: A combined model of the role of gesture in children's mathematical environments. *Frontiers in Psychology*, *12*. https://doi.org/10.3389/fpsyg.2021.650286

Gordon, R., Scalise, N. R., & Ramani, G. B. (2021). Give yourself a hand: The role of gesture and working memory in preschoolers' numerical knowledge. *Journal of Experimental Child Psychology*, *208*, 105145. https://doi.org/10.1016/j.jecp.2021.105145

Graham, T. A. (1999). The Role of gesture in children's learning to count. *Journal of Experimental Child Psychology*, *74*(4), 333–355. https://doi.org/10.1006/jecp.1999.2520

Groen, G. J., & Parkman, J. M. (1972). A chronometric analysis of simple addition. *Psychological Review*, *79*(4), 329–343. https://doi.org/10.1037/h0032950

Guarino, K., Wakefield, E., Morrison, R., & Richland, L. (2021). Exploring how visual attention, inhibitory control, and co-speech gesture instruction contribute to children's analogical reasoning ability. *Cognitive Development*, *58*, 101040. https://doi.org/10.1016/j.cogdev.2021.101040

Gunderson, E. A., Spaepen, E., Gibson, D., Goldin-Meadow, S., & Levine, S. C. (2015). Gesture as a window onto children's number knowledge. *Cognition*, 144, 14–28. https://doi.org/10.1016/j.cognition.2015.07.008

Hancock, G. R., & Mueller, R. O. (2013). *Structural equation modeling: A second course*. IAP.

Harrell Jr, F., & Dupont, C. (2021). *Hmisc: Harrell Miscellaneous*. https://CRAN.R-project.org/package=Hmisc

Harvey, H. A., & Miller, G. E. (2017). Executive function skills, early mathematics, and vocabulary in head start preschool children. *Early Education and Development*, *28*(3), 290–307. https://doi.org/10.1080/10409289.2016.1218728

Hill, F., Mammarella, I. C., Devine, A., Caviola, S., Passolunghi, M. C., & Szűcs, D. (2016). Maths anxiety in primary and secondary school students: Gender differences, developmental changes and anxiety specificity. *Learning and individual differences*, *48*, 45-53.

Holmes, J., & Gathercole, S. E. (2014). Taking working memory training from the laboratory into schools. *Educational Psychology*, 34(4), 440–450. https://doi.org/10.1080/01443410.2013.797338

Holmes, J., Gathercole, S. E., & Dunning, D. L. (2009). Adaptive training leads to sustained enhancement of poor working memory in children. *Developmental Science*, 12(4), F9–F15. https://doi.org/10.1111/j.1467-7687.2009.00848.x

Hooper, D., Coughlan, J., & Mullen, M. R. (2008). Structural equation modeling: Guidelines for determining model fit. *Electronic journal of business research methods*, *6*(1), pp53-60.

Hostetter, A. (2011). When do gestures communicate? A Meta-Analysis. *Psychological Bulletin*, *137*, 297–315. https://doi.org/10.1037/a0022128

Hostetter, A. B., & Alibali, M. W. (2008). Visible embodiment: Gestures as simulated action. *Psychonomic Bulletin & Review*, *15*(3), 495–514. https://doi.org/10.3758/PBR.15.3.495

Hu, L. & P.M. Bentler. 1999. Cutoff criteria for fit indexes in covariance structure analysis: conventional criteria versus new alternatives. *Struct. Equ. Model.* 6: 1–55.

Hughes, C., Ensor, R., Wilson, A., & Graham, A. (2009). Tracking executive function across the transition to school: A latent variable approach. *Developmental Neuropsychology*, *35*(1), 20–36. https://doi.org/10.1080/87565640903325691

Huttenlocher, J., Jordan, N. C., & Levine, S. C. (1994). A mental model for early arithmetic. *Journal of Experimental Psychology: General*, 284–296.

Imbo, I., & Vandierendonck, A. (2007). The development of strategy use in elementary school children: Working memory and individual differences. *Journal of Experimental Child Psychology*, 96(4), 284–309. https://doi.org/10.1016/j.jecp.2006.09.001

Iverson, J. M., & Goldin-Meadow, S. (1998). Why people gesture when they speak. *Nature*, *396*(6708), 228–228. https://doi.org/10.1038/24300

Jacob, R., & Parkinson, J. (2015). The potential for school-based interventions that target executive function to improve academic achievement: A review. *Review of Educational Research*, *85*(4), 512–552. https://doi.org/10.3102/0034654314561338

Jaeggi, S. M., Buschkuehl, M., Jonides, J., & Shah, P. (2012). Cogmed and working memory training—Current challenges and the search for underlying mechanisms. *Journal of Applied Research in Memory and Cognition*, 1(3), 211–213. https://doi.org/10.1016/j.jarmac.2012.07.002

Jordan, N. C., Huttenlocher, J., & Levine, S. C. (1992). Differential calculation abilities in young children from middle- and low-income families. *Developmental Psychology*, *28*(4), 644–653. https://doi.org/10.1037/0012-1649.28.4.644

Jordan, N. C., Kaplan, D., Ramineni, C., & Locuniak, M. N. (2009). Early math matters: Kindergarten number competence and later mathematics outcomes. *Developmental Psychology*, *45*(3), 850–867. https://doi.org/10.1037/a0014939

Jordan, N. C., Levine, S. C., & Huttenlocher, J. (1994). Development of calculation abilities in middle- and low-income children after formal instruction in school. *Journal of Applied Developmental Psychology*, *15*(2), 223–240. https://doi.org/10.1016/0193-3973(94)90014-0

Jorgensen, T. D., Pornprasertmanit, S., Schoemann, A. M., & Rosseel, Y. (2022). semTools: Useful tools for structural equation modeling. R package version 0.5-6. Retrieved from https://CRAN.R-project.org/package=semTools

Karbach, J., & Kray, J. (2009). How useful is executive control training? Age differences in near and far transfer of task-switching training: Transfer of task-switching training. *Developmental Science*, 12(6), 978–990. https://doi.org/10.1111/j.1467-7687.2009.00846.x

Kassambara, A. (2020). ggpubr: "ggplot2" Based Publication Ready Plots. https://CRAN.R-project.org/package=ggpubr

Kassambara, A. (2021). rstatix: Pipe-Friendly Framework for Basic Statistical Tests. https://CRAN.R-project.org/package=rstatix

Kelly, S. D., & Church, R. B. (1997). Can children detect conceptual information conveyed through other children's nonverbal behaviors. *Cognition and Instruction*, *15*(1), 107–134. https://doi.org/10.1207/s1532690xci1501_4

Kelly, S. D., & Church, R. B. (1998). A comparison between children's and adults' ability to detect conceptual information conveyed through representational gestures. *Child Development*, *69*(1), 85–93. https://doi.org/10.1111/j.1467-8624.1998.tb06135.x

Kelly, S. D., Singer, M., Hicks, J., & Goldin-Meadow, S. (2002). A helping hand in assessing children's knowledge: Instructing adults to attend to gesture. *Cognition and Instruction*, *20*(1), 1–26. https://doi.org/10.1207/S1532690XCI2001_1

Khng, K. H., & Lee, K. (2009). Inhibiting interference from prior knowledge: Arithmetic intrusions in algebra word problem solving. *Learning and Individual Differences*, *19*(2), 262–268. https://doi.org/10.1016/j.lindif.2009.01.004

Kominsky, J. F., Begus, K., Bass, I., Colantonio, J., Leonard, J. A., Mackey, A. P., & Bonawitz, E. (2021). Organizing the methodological toolbox: Lessons learned from implementing developmental methods online. *Frontiers in Psychology*, *12*, 4081. https://doi.org/10.3389/fpsyg.2021.702710

Kovács, Á. M., Tauzin, T., Téglás, E., Gergely, G., & Csibra, G. (2014). Pointing as epistemic request: 12-month-olds point to receive new information. *Infancy*, 19(6), 543–557. https://doi.org/10.1111/infa.12060

Krajewski, K., & Schneider, W. (2009). Early development of quantity to number-word linkage as a precursor of mathematical school achievement and mathematical difficulties: Findings from a four-year longitudinal study. *Learning and Instruction*, 19(6), 513–526. https://doi.org/10.1016/j.learninstruc.2008.10.002

Krauss, R. M. (1998). Why do we gesture when we speak? *Current Directions in Psychological Science*, *7*(2), 54–60.

Krauss, R. M., Dushay, R. A., Chen, Y., & Rauscher, F. (1995). The communicative value of conversational hand gesture. *Journal of Experimental Social Psychology*, *31*(6), 533–552. https://doi.org/10.1006/jesp.1995.1024

Kroesbergen, E. H., Van Luit, J. E. H., Van Lieshout, E. C. D. M., Van Loosbroek, E., & Van de Rijt, B. A. M. (2009). Individual differences in early numeracy: The role of executive functions and subitizing. *Journal of Psychoeducational Assessment*, *27*(3), 226–236. https://doi.org/10.1177/0734282908330586

Kroesbergen, E. H., van 't Noordende, J. E., & Kolkman, M. E. (2014). Training working memory in kindergarten children: Effects on working memory and early numeracy. *Child Neuropsychology*, *20*(1), 23–37. https://doi.org/10.1080/09297049.2012.736483

Kuhn, L. J., Willoughby, M. T., Wilbourn, M. P., Vernon-Feagans, L., Blair, C. B., & The Family Life Project Key Investigators. (2014). Early communicative gestures prospectively predict language development and executive function in early childhood. *Child Development*. https://doi.org/10.1111/cdev.12249

Lee, K., Ng, E. L., & Ng, S. F. (2009). The contributions of working memory and executive functioning to problem representation and solution generation in algebraic word problems. *Journal of Educational Psychology*, 101(2), 373–387. https://doi.org/10.1037/a0013843

Lee, K., Ng, S. F., Pe, M. L., Ang, S. Y., Hasshim, M. N. A. M., & Bull, R. (2012). The cognitive underpinnings of emerging mathematical skills: Executive functioning, patterns, numeracy, and arithmetic: Cognitive underpinnings. *British Journal of Educational Psychology*, *82*(1), 82–99. https://doi.org/10.1111/j.2044-8279.2010.02016.x

LeFevre, J.-A., Berrigan, L., Vendetti, C., Kamawar, D., Bisanz, J., Skwarchuk, S.-L., & Smith-Chant, B. L. (2013). The role of executive attention in the acquisition of mathematical skills for children in Grades 2 through 4. *Journal of Experimental Child Psychology, 114(2), 243–261*. https://doi.org/10.1016/j.jecp.2012.10.005

Lin, G. C., Wen, Z., Marsh, H. W., & Lin, H. S. (2010). Structural equation models of latent interactions: Clarification of orthogonalizing and double-mean-centering strategies. *Structural Equation Modeling*, *17*(3), 374-391.

Linzarini, A., Houdé, O., & Borst, G. (2015). When stroop helps Piaget: An inter-task positive priming paradigm in 9-year-old children. *Journal of Experimental Child Psychology*, *139*, 71–82. https://doi.org/10.1016/j.jecp.2015.05.010

Lubin, A., Poirel, N., Rossi, S., Lanoë, C., Pineau, A., & Houdé, O. (2010). Pedagogical effect of action on arithmetic performances in Wynn-like tasks solved by 2-year-olds. *Experimental Psychology*, *57*(6), 405–411. https://doi.org/10.1027/1618-3169/a000049

Lubin, A., Vidal, J., Lanoë, C., & Borst, G. (2013). Inhibitory control is needed for the resolution of arithmetic word problems: A developmental negative priming study. *Journal of Educational Psychology*. https://doi.org/10.1037/a0032625

Lutz, S., & Huitt, W. (2003). Information processing and memory: Theory and applications. *Educational Psychology Interactive*, 1-17.

Lyons, I. M., & Beilock, S. L. (2012). When math hurts: math anxiety predicts pain network activation in anticipation of doing math. *PloS one*, *7*(10), e48076.

Macleod, C. (2007). The concept of inhibition in cognition. *Inhibition in Cognition*. https://doi.org/10.1037/11587-001

Mareschal, D. (2016). The neuroscience of conceptual learning in science and mathematics. *Current Opinion in Behavioral Sciences*, 10, 114–118. https://doi.org/10.1016/j.cobeha.2016.06.001

Marstaller, L., & Burianová, H. (2013). Individual differences in the gesture effect on working memory. *Psychonomic Bulletin & Review*, *20*(3), 496–500. https://doi.org/10.3758/s13423-012-0365-0

Massonnié, J., Rogers, C. J., Mareschal, D., & Kirkham, N. Z. (2019). Is classroom noise always bad for children? The contribution of age and selective attention to creative performance in noise. *Frontiers in Psychology*, *10*, 381. https://doi.org/10.3389/fpsyg.2019.00381

McNeill, D. (1992). *Hand and mind: What gestures reveal about thought* (pp. xi, 416). University of Chicago Press.

Miyake, A., & Friedman, N. P. (2012). The nature and organization of individual differences in executive functions: Four general conclusions. *Current Directions in Psychological Science*, *21*(1), 8–14. https://doi.org/10.1177/0963721411429458

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex “frontal lobe” tasks: A latent variable analysis. *Cognitive Psychology*, *41*(1), 49–100. https://doi.org/10.1006/cogp.1999.0734

Monette, S., Bigras, M., & Guay, M.-C. (2011). The role of the executive functions in school achievement at the end of Grade 1. *Journal of Experimental Child Psychology*, *109*(2), 158–173. https://doi.org/10.1016/j.jecp.2011.01.008

Morrison, R. G., Doumas, L. A. A., & Richland, L. E. (2011). A computational account of children’s analogical reasoning: Balancing inhibitory control in working memory and relational representation: Development of analogical reasoning. *Developmental Science*, *14*(3), 516–529. https://doi.org/10.1111/j.1467-7687.2010.00999.x

Morsella, E., & Krauss, R. M. (2004). The role of gestures in spatial working memory and speech. *The American Journal of Psychology*, *117*(3), 411–424. https://doi.org/10.2307/4149008

Moshagen, M., & Erdfelder, E. (2016). A new strategy for testing structural equation models. *Structural Equation Modeling*, 23, 54–60. https://doi.org/10.1080/10705511.2014.950896

Müller, U., Kerns, K. A., & Konkin, K. (2012). Test–retest reliability and practice effects of executive function tasks in preschool children. *The Clinical Neuropsychologist*, *26*(2), 271–287. https://doi.org/10.1080/13854046.2011.645558

Navarro, J. I., Aguilar, M., Alcalde, C., Ruiz, G., Marchena, E., & Menacho, I. (2011). Inhibitory processes, working memory, phonological awareness, naming speed, and early arithmetic achievement. *The Spanish Journal of Psychology*, *14*(2), 580–588. https://doi.org/10.5209/rev_SJOP.2011.v14.n2.6

Nayfeld, I., Fuccillo, J., & Greenfield, D. B. (2013). Executive functions in early learning: Extending the relationship between executive functions and school readiness to science. *Learning and Individual Differences*, 26, 81–88. https://doi.org/10.1016/j.lindif.2013.04.011

Nigg, J. T. (2000). On inhibition/disinhibition in developmental psychopathology: Views from cognitive and personality psychology and a working inhibition taxonomy. *Psychological Bulletin*, *126*(2), 220–246. https://doi.org/10.1037/0033-2909.126.2.220

Novack, M. A., Congdon, E. L., Hemani-Lopez, N., & Goldin-Meadow, S. (2014). From action to abstraction: Using the hands to learn math. *Psychological Science*, *25*(4), 903–910. https://doi.org/10.1177/0956797613518351

OECD (2014), PISA 2012 Results: What students know and can do – Student performance in mathematics, reading and science (Volume I, Revised edition, February 2014), *PISA*, OECD Publishing. http://dx.doi.org/10.1787/9789264201118-en

O'Neill, G., & Miller, P. H. (2013). A show of hands: Relations between young children's gesturing and executive function. *Developmental psychology*, 49(8), 1517.

Özer, D., & Göksun, T. (2020). Visual-spatial and verbal abilities differentially affect processing of gestural vs. Spoken expressions. *Language, Cognition and Neuroscience*, 35(7), 896–914. https://doi.org/10.1080/23273798.2019.1703016

Özçalışkan, Ş., & Goldin-Meadow, S. (2010). Sex differences in language first appear in gesture. *Developmental science*, 13(5), 752-760.

Park, D., Ramirez, G., & Beilock, S. L. (2014). The role of expressive writing in math anxiety. *Journal of Experimental Psychology: Applied*, *20*(2), 103.

Passolunghi, M. C., & Siegel, L. (2001). Short-term memory, working memory, and inhibitory control in children with difficulties in arithmetic problem solving. *Journal of Experimental Child Psychology*, *80*, 44–57. https://doi.org/10.1006/jecp.2000.2626

Pellegrino, J. W., & Goldman, S. R. (1987). Information processing and elementary mathematics. *Journal of Learning Disabilities*, *20*(1), 23–32. https://doi.org/10.1177/002221948702000105

Peng, P., Namkung, J., Barnes, M., & Sun, C. (2016). A meta-analysis of mathematics and working memory: Moderating effects of working memory domain, type of mathematics skill, and sample characteristics. *Journal of Educational Psychology*, *108*(4), 455–473. https://doi.org/10.1037/edu0000079

Perry, M., Church, R.B., & Goldin-Meadow, S. (1988). Transitional knowledge in the acquisition of concepts. *Cognitive Development*, 3(4), 359–400. https://doi.org/10.1016/0885-2014(88)90021-4

Pesenti, M., Thioux, M., Seron, X., & Volder, A. D. (2000). Neuroanatomical Substrates of Arabic Number Processing, Numerical Comparison, and Simple Addition: A PET Study. *Journal of Cognitive Neuroscience*, *12*(3), 20.

Pinel, P., Piazza, M., Le Bihan, D., & Dehaene, S. (2004). Distributed and overlapping cerebral representations of number, size, and luminance during comparative judgments. *Neuron, 41*(6), 983–993. https://doi.org/10.1016/S0896-6273(04)00107-2

Ping, R. M., & Goldin-Meadow, S. (2008). Hands in the air: Using ungrounded iconic gestures to teach children conservation of quantity. *Developmental Psychology*, *44*(5), 1277–1287. https://doi.org/10.1037/0012-1649.44.5.1277

Ping, R., & Goldin-Meadow, S. (2010). Gesturing saves cognitive resources when talking about non present objects. *Cognitive Science*, *34*(4), 602–619. https://doi.org/10.1111/j.1551-6709.2010.01102.x

Pouw, W. T. J. L., Mavilidi, M.-F., van Gog, T., & Paas, F. (2016). Gesturing during mental problem solving reduces eye movements, especially for individuals with lower visual working memory capacity. *Cognitive Processing*, 17(3), 269–277. https://doi.org/10.1007/s10339-016-0757-6

Prather, R. W., & Alibali, M. W. (2009). The development of arithmetic principle knowledge: How do we know what learners know? *Developmental Review*, *29*(4), 221–248. https://doi.org/10.1016/j.dr.2009.09.001

Prather, R., & Alibali, M. W. (2011). Children's acquisition of arithmetic principles: The role of experience. *Journal of Cognition and Development*, *12*(3), 332–354. https://doi.org/10.1080/15248372.2010.542214

Purpura, D. J., Schmitt, S. A., & Ganley, C. M. (2017). Foundations of mathematics and literacy: The role of executive functioning components. *Journal of Experimental Child Psychology*, *153*, 15–34. https://doi.org/10.1016/j.jecp.2016.08.010

R Core Team. (2020). R: A language and environment for statistical computing. Vienna, Austria.

Ramani, G. B., Daubert, E. N., Lin, G. C., Kamarsu, S., Wodzinski, A., & Jaeggi, S. M. (2020). Racing dragons and remembering aliens: Benefits of playing number and working memory games on kindergartners' numerical knowledge. *Developmental Science*, *23*(4).

https://doi.org/10.1111/desc.12908

Ramani, G. B., Daubert, E. N., & Scalise, N. R. (2019). Role of play and games in building children's foundational numerical knowledge. In *Cognitive Foundations for Improving Mathematical Learning* (pp. 69–90). Elsevier. https://doi.org/10.1016/B978-0-12-815952-1.00003-7

Ramani, G. B., Jaeggi, S. M., Daubert, E. N., & Buschkuehl, M. (2017). Domain-specific and domain-general training to improve kindergarten children's mathematics. *Journal of Numerical Cognition*, *3*(2), 468–495. https://doi.org/10.5964/jnc.v3i2.31

Ramani, G. B., & Siegler, R. S. (2008). Promoting broad and stable improvements in low-income children's numerical knowledge through playing number board games. *Child Development*, *79*(2), 375–394. https://doi.org/10.1111/j.1467-8624.2007.01131.x

Ramirez, G., Chang, H., Maloney, E. A., Levine, S. C., & Beilock, S. L. (2016). On the relationship between math anxiety and math achievement in early elementary school: The role of problem solving strategies. Journal of Experimental Child Psychology, 141, 83–100. doi:10.1016/j.jecp.2015.07.014 10.1016/j.jecp.2015.07.014

Reynolds, F. J., & Reeve, R. A. (2001). Gesture in collaborative mathematics problem-solving. *The Journal of Mathematical Behavior*, 20(4), 447-460.

Rhoads, C. L., Miller, P. H., & Jaeger, G. O. (2018). Put your hands up! Gesturing improves preschoolers' executive function. *Journal of Experimental Child Psychology*, 173, 41–58. https://doi.org/10.1016/j.jecp.2018.03.010

Rosseel, Y (2012). lavaan: An R package for structural equation Modeling. *Journal of Statistical Software,* 48(2), 1–36. doi:10.18637/jss.v048.i02.

Rosseel, Y. (2018). "Lavaan: Latent variable analysis." Retrieved from https://CRAN.R-project.org/package= lavaan

Ritchie, S. J., & Bates, T. C. (2013). Enduring links from childhood mathematics and reading achievement to adult socioeconomic status. *Psychological Science*, *24*(7), 1301–1308. https://doi.org/10.1177/0956797612466268

Robinson, K. M., & Dubé, A. K. (2013). Children's additive concepts: Promoting understanding and the role of inhibition. *Learning and Individual Differences*, *23*, 101–107. https://doi.org/10.1016/j.lindif.2012.07.016

Rohlfing, K. J., Longo, M. R., & Bertenthal, B. I. (2012). Dynamic pointing triggers shifts of visual attention in young infants. *Developmental Science,* 15(3), 426–435. https://doi.org/10.1111/j.1467-7687.2012.01139.x

Rueda, M. R., Posner, M. I., & Rothbart, M. K. (2011). Attentional control and self-regulation. In *Handbook of self-regulation: Research, theory, and applications, 2nd ed.* (pp. 284–299). Guilford Press.

Satorra, A., & Bentler, P. M. (2010). Ensuring positiveness of the scaled difference chi-square test statistic. *Psychometrika*, *75*(2), 243-248.

Schumacker, R. E., & Lomax, R. G. (2010). *A beginner's guide to structural equation modeling (3rd ed.)*. New York, NY: Routledge Academic.

Schoemann, A.M.; Jorgensen, T.D. Testing and interpreting latent variable interactions using the semTools Package. Psych 2021, 3, 322–335. https://doi.org/10.3390/ psych3030024

Shapiro, L. (2019). *Embodied Cognition* (2nd ed.). Routledge. https://doi.org/10.4324/9781315180380

Shipstead, Z., Redick, T. S., & Engle, R. W. (2012). Is working memory training effective? *Psychological Bulletin*, 138(4), 628–654. https://doi.org/10.1037/a0027473

Shrager, J., & Siegler, R. S. (1998). SCADS: A model of children’s strategy choices and strategy discoveries. *Psychological Science*, *9*(5), 405–410.

Siegler, R. S. (1987). Some general conclusions about children’s strategy choice procedures. *International Journal of Psychology*, 22(5–6), 729–749. https://doi.org/10.1080/00207598708246800

Siegler, R. S. (1987). The perils of averaging data over strategies: An example from children’s addition. *Journal of Experimental Psychology: General*, 116, 250–264. https://doi.org/10.1037/0096-3445.116.3.250

Siegler, R. S. (1996). *Emerging Minds: The Process of Change in Children’s Thinking*. Oxford University Press. https://doi.org/10.1093/oso/9780195077872.001.0001

Siegler, R. S., & Araya, R. (2005). A computational model of conscious and unconscious strategy discovery. In R. V. Kail (Ed.), *Advances in Child Development and Behavior* (Vol. 33, pp. 1–42). JAI. https://doi.org/10.1016/S0065-2407(05)80003-5

Siegler, R. S., & Jenkins, E. A. (2014). How Children Discover New Strategies. *Psychology Press*. https://doi.org/10.4324/9781315807744

Siegler, R. S., & Shrager, J. (1984). Strategy choices in addition and subtraction: How do children know what to do? In C. *Origins of Cognitive Skills.*

Singer, M. A., & Goldin-Meadow, S. (2005). Children learn when their teacher’s gestures and speech differ. *Psychological Science*, *16*(2), 85–89. https://doi.org/10.1111/j.0956-7976.2005.00786.x

St. Clair-Thompson, H. L., & Gathercole, S. E. (2006). Executive functions and achievements in school: Shifting, updating, inhibition, and working memory. *Quarterly Journal of Experimental Psychology*, *59*(4), 745–759. https://doi.org/10.1080/17470210500162854

St Clair-Thompson, H., Stevens, R., Hunt, A., & Bolder, E. (2010). Improving children's working memory and classroom performance. *Educational Psychology*, 30(2), 203–219. https://doi.org/10.1080/01443410903509259

Stieff, M., Lira, M. E., & Scopelitis, S. A. (2016). Gesture supports spatial thinking in STEM. *Cognition and Instruction*, *34*(2), 80-99.

Swanson, H. L. (2006). Cross-sectional and incremental changes in working memory and mathematical problem solving. *Journal of Educational Psychology*, *98*(2), 265–281. https://doi.org/10.1037/0022-0663.98.2.265

Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science*, *12*(2), 257–285. https://doi.org/10.1016/0364-0213(88)90023-7

Thorell, L. B. (2007). Do delay aversion and executive function deficits make distinct contributions to the functional impact of ADHD symptoms? A study of early academic skill deficits. *Journal of Child Psychology and Psychiatry*, *48*(11), 1061–1070. https://doi.org/10.1111/j.1469-7610.2007.01777.x

Tomasello, M., Carpenter, M., & Liszkowski, U. (2007). A new look at infant pointing. *Child Development*, 78(3), 705–722. https://doi.org/10.1111/j.1467-8624.2007.01025.x

Valenzeno, L., Alibali, M. W., & Klatzky, R. (2003). Teachers' gestures facilitate students' learning: A lesson in symmetry. *Contemporary Educational Psychology*, *28*(2), 187–204. https://doi.org/10.1016/S0361-476X(02)00007-3

Van der Ven, S. H. G., Kroesbergen, E. H., Boom, J., & Leseman, P. P. M. (2012). The development of executive functions and early mathematics: A dynamic relationship: Development executive functions mathematics. *British Journal of Educational Psychology*, *82*(1), 100–119. https://doi.org/10.1111/j.2044-8279.2011.02035.x

Vosniadou, S., Pnevmatikos, D., & Makris, N. (2018). The role of executive function in the construction and employment of scientific and mathematical concepts that require conceptual change learning. *Neuroeducation*, 5, 62–72. https://doi.org/10.24046/neuroed.20180502.62

Visu-Petra, L., Cheie, L., Benga, O., & Miclea, M. (2011). Cognitive control goes to school: The impact of executive functions on academic performance. *Procedia - Social and Behavioral Sciences*, *11*, 240–244. https://doi.org/10.1016/j.sbspro.2011.01.069

Wagner, S. M., Nusbaum, H., & Goldin-Meadow, S. (2004). Probing the mental representation of gesture: Is handwaving spatial? *Journal of Memory and Language*, *50*(4), 395–407. https://doi.org/10.1016/j.jml.2004.01.002

Wakefield, E. M. [1], Carrazza, C.[1], Hemani-Lopez, N., Plath, K., & Goldin-Meadow, S. (2021). Children integrate speech and gesture across a wider temporal window than speech and action when learning a math concept. *Cognition*, *210*, 104604. https://doi.org/10.1016/j.cognition.2021.104604

Wakefield, E., Novack, M. A., Congdon, E. L., Franconeri, S., & Goldin-Meadow, S. (2018). Gesture helps learners learn, but not merely by guiding their visual attention. *Developmental Science*, 21(6), e12664. https://doi.org/10.1111/desc.12664

Wakefield, E. M., Congdon, E. L., Novack, M. A., Goldin-Meadow, S., & James, K. H. (2019). Learning math by hand: The neural effects of gesture-based instruction in 8-year-old children. *Attention, Perception, & Psychophysics*, *81*(7), 2343–2353. https://doi.org/10.3758/s13414-019-01755-y

Wakefield, E., & James, K. (2015). Effects of learning with gesture on children’s understanding of a new language concept. *Developmental Psychology*, *51*, 1105–1114.

https://doi.org/10.1037/a0039471

Watts, T. W., Duncan, G. J., Siegler, R. S., & Davis-Kean, P. E. (2014). What's past is prologue: Relations between early mathematics knowledge and high school achievement. *Educational Researcher*, *43*(7), 352–360. https://doi.org/10.3102/0013189X14553660

Wickham, H. (2016). ggplot2: elegant graphics for data analysis. Springer-Verlag, New York. https://ggplot2.tidyverse.org

Wickham, H., & Bryan, J. (2019). readxl: Read Excel Files. https://CRAN.R-project.org/package=readxl

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T., Miller, E., Bache, S., Müller, K., Ooms, J., Robinson, D., Seidel, D., Spinu, V., … Yutani, H. (2019). Welcome to the Tidyverse. *Journal of Open Source Software*, *4*(43), 1686. https://doi.org/10.21105/joss.01686

Wiebe, S. A., Espy, K. A., & Charak, D. (2008). Using confirmatory factor analysis to understand executive control in preschool children: I. Latent structure. *Developmental Psychology*, *44*(2), 575–587. https://doi.org/10.1037/0012-1649.44.2.575

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review*, *9*(4), 625–636. https://doi.org/10.3758/BF03196322

Wilkey, E. D., & Price, G. R. (2019). Attention to number: The convergence of numerical magnitude processing, attention, and mathematics in the inferior frontal gyrus. *Human Brain Mapping*, *40*(3), 928–943. https://doi.org/10.1002/hbm.24422

Worthington, R. L., & Whittaker, T. A. (2006). Scale development research: A content analysis and recommendations for best practices. *The counseling psychologist*, *34*(6), 806-838.

Wu, Y. C., & Coulson, S. (2014). Co-speech iconic gestures and visuo-spatial working memory. *Acta Psychologica*, 153, 39–50. https://doi.org/10.1016/j.actpsy.2014.09.002

Wu, Y. C., & Coulson, S. (2014). A Psychometric Measure of Working Memory Capacity for Configured Body Movement. *PLoS ONE*, 9(1), e84834. https://doi.org/10.1371/journal.pone.0084834

Wynn, K., Carter, N. S., & Fairlamb, A. H. (1992). Addition and subtraction by human infants. *Nature*, *358*(6389), 749-750.

Xenidou-Dervou, I., De Smedt, B., van der Schoot, M., & van Lieshout, E. C. D. M. (2013). Individual differences in kindergarten math achievement: The integrative roles of approximation skills and working memory. *Learning and Individual Differences*, 28, 119–129. https://doi.org/10.1016/j.lindif.2013.09.012

Young, C. B., Wu, S. S., & Menon, V. (2012). The neurodevelopmental basis of math anxiety. *Psychological science*, *23*(5), 492-501.

Zelazo, P. D., Anderson, J. E., Richler, J., Wallner-Allen, K., Beaumont, J. L., & Weintraub, S. (2013). Ii. Nih toolbox cognition battery (cb): Measuring executive function and attention. *Monographs of the Society for Research in Child Development*, *78*(4), 16–33. https://doi.org/10.1111/mono.12032

Zaitchik, D., Iqbal, Y., & Carey, S. (2014). The effect of executive function on biological reasoning in young children: An individual differences study. *Child Development*, 85(1), 160–175. https://doi.org/10.1111/cdev.12145

Zheng, X., Swanson, H. L., & Marcoulides, G. A. (2011). Working memory components as predictors of children’s mathematical word problem solving. *Journal of Experimental Child Psychology*, *110*(4), 481–498. https://doi.org/10.1016/j.jecp.2011.06.001