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USING PARASYMPATHETIC ACTIVITY TO GAIN INSIGHTS INTO GESTURE AND LEARNING

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ABSTRACT

Children learn mathematics better when allowed to use their hands to gesture—whether gesturing spontaneously or instructed to produce specific gestures (Broaders et al., 2007; Cook & Goldin-Meadow, 2006). One proposed mechanism for why gesturing enhances learning is that it lightens cognitive load. In this dissertation, I use a measure of parasympathetic activity (respiratory sinus arrhythmia) to infer changes in cognitive load throughout the learning process. Using this unobtrusive method, I investigate differences in explicit understanding of math equivalence and implicit knowledge reflected in gesture-speech mismatches (chapter 1), differences in cognitive load during spontaneous versus instructed gesture (chapter 2), and effects of instructed gesture on learning for children with varying levels of cognitive load imposed by anxious thoughts about math (chapter 3). In my final chapter I examine parasympathetic activity while children solve problems in order to identify potential differences in cognitive processing between children who learn a mathematical concept and those whose knowledge stays the same over time (chapter 4). My most intriguing findings suggest that gesture-speech mismatch is a person-level characteristic, as opposed to a problem-level state; that gesture instruction is particularly beneficial for children with higher levels of math anxiety; and that there is a parasympathetic signature of learning that sticks and remains stable over time, compared to learning that fades.

INTRODUCTION

When we talk, we move our hands. People gesture across all cultures (Feyereisen & Lannoy, 1991) and ages (Iverson & Goldin-Meadow, 1998a)—even when they have been blind from birth and have never seen anyone else gesture (Iverson & Goldin-Meadow, 1998b). To the naïve observer, gestures may appear to be meaningless hand waving, but decades of research have shown that the gestures speakers spontaneously produce when they talk can reflect substantive ideas relevant to a task at hand (Kendon, 1983; McNeill, 1992; Goldin-Meadow, 2003). The relationship between a speaker's hands and mind is bidirectional—gestures not only *reflect* a speaker's knowledge (Church & Goldin-Meadow, 1986; Goldin-Meadow, Alibali, & Church, 1993; Perry, et al., 1988), but can also *change* knowledge (Stevanoni & Salmon, 2005; Cook & Goldin-Meadow, 2006; Broaders, Cook, Mitchell, & Goldin-Meadow, 2007; de Ruiter, 1998; Krauss, Chen, & Chawla, 1996; Alibali & DiRusso, 1999; Rime, Shiaratura, Hupet, & Ghysselinckx, 1984).

Gestures are powerful at shaping cognition in educational settings. Given its spatial nature, gesture has been used as a tool for learning STEM concepts (science, technology, engineering, and math), including mathematical equivalence, conservation of quantity, and organic chemistry (e.g., Broaders et al., 2007; Ping & Goldin-Meadow, 2008; Ping et al., 2012). Gesture has been shown to enhance the learning of new material for both children and adults. Viewing a teacher's lesson containing gesture can help students learn and maintain information, compared to viewing a lesson containing speech alone (Cook et al., 2013; Church et al., 2004; Valenzeno et al., 2003; Ping & Goldin-Meadow, 2008; Singer & Goldin-Meadow, 2005). Producing gestures can also enhance learning, both when learners spontaneously produce the gestures and when they are instructed to gesture (Broaders et al., 2007; Cook & Goldin-Meadow, 2006). Researchers theorize that gesturing may allow for greater understanding of the concept at hand by providing students with a physical medium with which to experience and express knowledge.

Spontaneous gesture-speech mismatches reflect knowledge

Although gestures typically reinforce their accompanying speech, the information that gesture conveys is not always redundant with speech -- a speaker's gestures often reveal information not found anywhere in his or her speech. For example, consider a child shown two tall, thin glasses containing the same amount of water. The water in one glass is poured into a short wide dish and the child is asked whether the dish has the same amount of water as the full glass. The child says "no" and justifies his incorrect belief by saying "it's different because this one's tall and that one's short,"— but in gesture produces SKINNY (two flat palms held at the sides of the glass) and then WIDE (two flat palms held at the sides of the dish). This child highlights height in his speech but width in his gesture. Such cases where gestures contain different, though not unrelated, information from that in speech have been called *gesture-speech mismatches*. By examining both what a child says verbally and what he or she gestures, investigators can gain insight into the number and kinds of strategies that a child considers in solving a problem (Church & Goldin-Meadow, 1986; Goldin-Meadow, Alibali, & Church, 1993; Perry et al., 1988; Goldin-Meadow, Nusbaum, Garber, & Church, 1993).

Gesture-speech mismatches were first identified by Church & Goldin-Meadow (1986), who observed 5- to 8-year-old children solving conservation problems like in the above example. They noticed that some children, whom they labeled "discordant," produced many explanations in which the information they conveyed in speech did not match the information conveyed in gesture, while other "concordant" children produced few mismatched explanations. The discordant children often expressed more than one strategy for solving conservation tasks -- one in speech and a different one in gesture -- and in this sense entertained multiple strategies with respect to the tasks. They hypothesized that gesture-speech mismatches reflect a basic inconsistency in the explanatory system that underlies a child's understanding of a concept. Attending to explanations in both speech and gesture can reveal both what a child knows and how consistently the child knows it.

Since Church and Goldin-Meadow (1986) discovered the phenomenon, gesture-speech mismatches have been observed and investigated in children's and adults' explanations of a variety of other concepts. These include infants acquiring words (Gershkoff-Stowe & Smith, 1991), preschoolers learning to count (Graham, 1994), elementary school children reasoning about mathematics problems (Perry et al., 1988; Alibali & Goldin-Meadow, 1993), middle-schoolers reasoning about seasonal change (Crowder & Newman, 1993), children and adults reasoning about moral dilemmas (Goodman, Church, & Schonert-Reichl, 1991), adults explaining choice points in the Tower of Hanoi problem solving task (Garber & Goldin-Meadow, 2002), adolescents reasoning about Piagetian bending rods tasks (Stone, Webb, & Mahootian, 1991), adults reasoning about gears (Perry & Elder, 1997), and adults reasoning about algebra and physics story problems (Alibali, Bassok, Olseth, Syc, & Goldin-Meadow, 1999). Mismatches between the information conveyed in gesture and American Sign Language ("gesture-sign mismatches") have also been identified in Deaf students learning mathematical equivalence (Goldin-Meadow, Shield, Lenzen, Herzig, & Padden, 2012).

In addition to being a useful marker of inconsistent knowledge about a given concept, gesture-speech mismatch has also been shown to be an index of cognitive transition. The transitional knowledge state is often identified post hoc—any child who learns from instruction is said to have been in a transitional state during that instruction (e.g., Vygotsky, 1962; Strauss, 1972; Gelman, 1969). While it can be useful to retrospectively identify differences between children who did and did not learn, it can also be valuable to identify markers in the transitional state that can be used predictively. Gesture-speech mismatches can be one such marker for determining whether or not a child has unintegrated knowledge. Children can be considered transitional if they exhibit unintegrated levels of understanding, which suggests they are ready to progress to a new level of understanding of a concept (Beilin, 1965; Piaget, 1967; Strauss, 1972). The notion of learning "readiness" corresponds to children who have knowledge of the component parts of a concept, but have not yet integrated those components and mastered the entire concept (e.g., Siegler, 1976). For example, children who possess all of the component skills necessary to read are said to be "reading ready" and read earlier than children without these component skills (Wagner & Torgesen, 1987).

Evidence that the discordant state is transitional comes from Wagner, Scott, Church, and Goldin-Meadow (1990), who showed that children begin their acquisition of mathematical equivalence in a concordant state (albeit an incorrect one), then proceed through a period of discordance, and then return to a concordant (and correct) state. Building off of this work, Alibali and Goldin-Meadow (1993) found that children pass through a series of knowledge states beginning with a single, incorrect strategy about equivalence, characterized by a gesture-speech match, followed by a transitional knowledge state in which children consider multiple strategies, as revealed in gesture-speech mismatches. Children eventually close in on a single, correct strategy, as seen with another gesture-speech match at a higher knowledge level. This provides further evidence that transitional knowledge of a concept is characterized by variability in performance on a single problem, which is reflected in gesture-speech mismatch.

The discordant state characterized by gesture-speech mismatch is transitional not only in the sense that it is both preceded and followed by a concordant state, but also in terms of a heightened receptivity to instruction. Transitional knowledge states have often been associated with the notion of receptivity to environmental input. Researchers have hypothesized that children in a transitional state do not yet have consistent knowledge of a concept, yet their underlying cognitive structures are sufficiently developed to allow them to accommodate new information in that concept (Beilin, 1965; Brainerd, 1972; Langer & Strauss, 1972; Murray, 1974; Strauss & Langer, 1970; Strauss & Rimalt, 1974). Siegler (1996) argues that cognitive variability is an essential component of development and that learning arises from a state where one has many different strategies in one's problem-solving repertoire. The transitional child is considered to possess a primordial version of a newly developing concept, and transitional knowledge has been described as a budding structure that is ready to bloom (Beilin, 1965; Brainerd, 1977; Vygotsky, 1978). Gesture-speech mismatch provides a way to operationalize this illusive transitional state. Since children who produce mismatches while explaining a given concept have pieces of information that they have not yet consolidated into a coherent explanatory system, they might particularly benefit from instruction that helps them consolidate their knowledge in that concept.

Many studies have provided evidence for this hypothesis that gesture-speech mismatchers are more ready to learn than non-mismatchers. In their seminal study, Church and Goldin-Meadow (1986) found that children who frequently produced gesture-speech mismatches when explaining conservation were more likely to benefit from training in conservation than children who infrequently or never produced mismatches. Perry, Church, and Goldin-Meadow (1988) replicated this finding in a mathematical equivalence paradigm, in which mismatchers were more responsive to training in equivalence than were non-mismatchers. This relation between mismatch and learning has also been found in other age groups and domains, including 5- to 9-year-old children learning about balance (Pine, Lufkin, & Messer, 2004), adults learning a gears task (Perry & Elder, 1997), and even in more naturalistic learning situations such as toddlers learning their first word combinations (Butcher & Goldin-Meadow, 2003; Iverson & Goldin-Meadow, 2005) and school-aged children learning a mathematical concept from a teacher (Goldin-Meadow & Singer, 2003).

It is important to note that gesture-speech mismatch is not a general characteristic of a child, but rather describes a child's inconsistent knowledge state and trainability with respect to a particular concept. For example, a child who produces gesture-speech mismatches in explanations about mathematical equivalence does not express multiple strategies while explaining a concept with which he or she is more familiar (Perry et al., 1988). Gesture-speech mismatch can thus serve as a technique for determining when a child is most receptive to environmental input, which stimulates change from one level of understanding of a concept to the next.

While mismatches in naturalistic environments may indirectly shape learning through signaling a speaker's knowledge to others (Singer & Goldin-Meadow, 2003), past work suggests that gestures can also play a direct role in the process of thinking and hence *change* knowledge. The act of producing a gesture-speech mismatch may in fact provide the impetus for change in a child's acquisition of a concept. The most commonly proposed mechanism through which producing gesture-speech mismatches changes knowledge is through creating a state of uncertainty or conflict that motivates the child to learn. Theories positing internal conflict as a mechanism of developmental change exist across multiple traditions (Halford, 1970; Siegler, 1984; Wilkinson, 1982; Ames & Murray, 1982; Murray, 1982; Riegel, 1975; Keil, 1984; Klahr, 1984; Piaget, 1967). They all assume that children in transition with respect to a given concept have variable rules or strategies in mind for how to solve a problem, which, at some level, they must consider and compare (albeit probably not consciously) in order to detect discrepancies and advance to a more stable understanding of the concept. Activating these conflicting beliefs may create an uncomfortable state of dissonance, which can serve as a catalyst for change to resolve this tension (Harmon-Jones & Amodio, 2009).

Goldin-Meadow, Nusbaum, Garber, & Church (1993) found evidence that mismatchers are not just vacillating between different strategies on different problems, but rather are spontaneously entertaining two different strategies *simultaneously* on a given problem. Moreover, this simultaneous activation of more than one notion is not only evident in mismatchers' explanations of a concept, but also in their solutions to problems instantiating that concept. Perry and colleagues (1988) argue that this simultaneous production allows mismatchers to more easily consider the relationship--and potential conflict--between two strategies.

For example, consider a child explaining how to solve the problem 5 + 8 + 2 = __ + 2. She expresses an "add-to-equal" strategy in speech, saying "I added the 5, 8, and 2," but simultaneously produces an "add-all" strategy in gesture, pointing at all four numbers in the problem. These two strategies lead to incompatible (and incorrect) solutions--the first strategy would result in an answer of 15, whereas the second strategy results in an answer of 17. The conflict between these two strategies may be more apparent when experienced simultaneously across modalities or representational formats. Awareness of this conflict, on an explicit or implicit level, may play an important role in pushing the child toward an understanding of equivalence, and hence explain why mismatchers are more likely to learn.

Knowledge expressed in spontaneous gesture

An important aspect of mismatches is whether or not they convey explicit or implicit knowledge. When observing gesture-speech mismatches, it can be unclear whether or not a speaker has conscious access to the meaning conveyed in his or her movements. Speakers often use their hands to add information to their verbal message (e.g., saying “the boy went down the slide” while producing a spiral motion with the hand to clarify that it was a spiral slide). In such cases, the speaker clearly has knowledge about the spiral nature of the slide he or she is describing, but can save words by putting some information into a second modality. However, sometimes speakers may be able to gesture about a concept before they can verbalize it.

One way to assess whether gesture-speech mismatchers have conscious access to the knowledge conveyed in their gestures is to look to see if that information also occurs in their other spoken explanations (i.e., explanations produced at another time). In studies examining gesture-speech mismatch about mathematical equivalence, children who convey a particular strategy in gesture in a mismatch on one math problem generally do not convey that strategy in speech on any problems (Goldin-Meadow, Alibali, & Church, 1993; Alibali & Goldin-Meadow, 1993; Goldin-Meadow & Alibali, 1995). However, many of the strategies expressed only in gesture during pre-training explanations appear in children’s post-training spoken explanations. This suggests that mismatchers have some implicit understanding of quantity invariance before training that is not yet integrated into their verbal explanations (Perry et al., 1988). Training, in some cases extremely minimal, seems to help make this implicit knowledge explicit (Gelman & Baillargeon, 1983; Church & Goldin-Meadow, 1986).

However, just because mismatchers do not articulate the information expressed in their gestures does not necessarily mean the knowledge is implicit. Garber, Alibali, and Goldin-Meadow (1998) asked whether children can recognize the knowledge conveyed in their gestures in another context. They identified the strategies expressed only in gesture during children's explanations of mathematical equivalence and then gave children a task in which they were asked to rate the acceptability of a variety of solutions to a second set of equivalence problems. They found that children judged procedures that they had expressed uniquely in gesture on the explanation task as more acceptable than procedures they had not expressed. The authors conclude that the emerging knowledge initially expressed only in gesture is neither fully implicit nor fully explicit.

Rather, they argue that the gestural information contained in mismatches represents a middle point along a continuum of knowledge states ranging from fully implicit and embedded in problem-solving procedures to fully explicit and accessible to verbal report (Goldin-Meadow & Alibali, 1994). The knowledge is not fully implicit, since children can apply it in another task, but it is also not fully explicit, since it often does not appear in verbal reports. Their finding that children rated solutions derived from procedures they expressed in gesture lower than solutions derived from procedures they had expressed in speech further suggests that gesture is not as accessible as knowledge that can be verbalized. The researchers propose that the developmental course for transforming symbolic, non-verbal knowledge into a verbalizable format is not merely a process of "translating" gesture into words. If it were, the state of readiness in the mismatching child would not be necessary for the transformation process to take place (Alibali & Goldin-Meadow, 1993; Goldin- Meadow et al., 1993). Instead, the knowledge must be re-encoded and transformed from a format that is easily conveyed in gesture into the codified format that speech demands. Hence, being able to convey knowledge in gesture marks an important step along the path to full understanding.

Instructed gesture production changes knowledge

In addition to spontaneous production of gesture-speech mismatches, forced gesturing also plays an important role in learning. A 2009 study by Goldin-Meadow, Cook and Mitchell manipulated the hand movements produced by third and fourth graders during a lesson about mathematical equivalence, which has been shown to be crucial for later understanding of early algebra (Byrd et al., 2015). Children who were unable to solve pretest problems (e.g., 2 + 3 + 8 = __ + 8) were randomly assigned to one of three groups, each with its own learning strategy. Children in the "Correct Gesture" condition were taught to say "I want to make one side equal to the other side" while producing a grouping strategy in gesture. The "Partially Correct" group was taught the same words and grouping gesture but gestured to the wrong numbers. The third group was taught the speech alone with no gesture. Everyone then used their new strategy to solve six problems with no feedback. Children taught the correct grouping gesture were more likely to succeed on a posttest after training than children taught the partially correct gesture or no gesture at all. This effect was mediated by whether children added the grouping strategy to their post-lesson spoken explanation of how they solved the problems. Since the grouping strategy was only expressed in the gesture, this suggests that children incorporated information from their movements into their explicit understanding of the problems. Interestingly, the group who pointed at the wrong numbers learned more than children who didn't use their hands at all, which suggests that gesture does not just help by directing attention to relevant numbers—specific aspects of the movements must be conveying information that helps children learn.

Cognitive load and its measurement

Another proposed mechanism for why gesturing enhances learning, which I will be exploring throughout this dissertation, is that it helps lighten cognitive load. Cognitive load, also known as mental workload, refers to the amount of information processing activity imposed on working memory (Miller, 1956; Sweller, 1988). Working memory is an important cognitive construct involved in maintaining relevant information in a highly active state and inhibiting interfering information (Engle, 2002; Baddeley & Hitch, 1974). Higher cognitive load is associated with greater task difficulty, as more difficult tasks require greater attention and cognitive processing (Cowan, 1995). Cognitive load by itself cannot be used to predict achievement for a given task. For example, high cognitive load is positively associated with performance when reflecting greater involvement, motivation, and effort in a task (MacKinnon, Geiselman, & Woodward, 1985). However, high cognitive load can result in lower performance when it reflects cognitive interferences such as anxious thoughts (Ashcraft, 1998; Baddeley & Hitch, 1974; Ramirez et al., 2013).

Physiological measures allow researchers to gather real-time, continuous, and relatively unobtrusive measures of cognitive load (Prinzel, Freeman, Scerbo, Mikulka, & Pope, 2000). It is well established that mental states are associated with automatic, physiological responses (Quigley & Barrett, 2014). Varying task difficulty influences many psychophysiological signals including galvanic skin response (GSR, Ikehara & Crosby, 2005; Shi, Ruiz, Taib, Choi, & Chen, 2007), pupillary responses, eye movements, and blink interval (Beatty & Lucero-Wagoner, 2000; Ikehara & Crosby, 2005; Iqbal, Adamczyk, Zheng, & Bailey, 2005; Wilson, 2002), electroencephalogram (EEG or brainwave levels, Kilseop & Rohae, 2005; Wilson, 2002), electrocardiogram (ECG, Kilseop & Rohae, 2005), respiration (Mulder, 1992), and heart rate and heart rate variability (Fredericks, Choi, Hart, Butt, & Mital, 2005; Mulder, 1992; Wilson, 2002).

In particular, the effects of mental workload on the autonomic nervous system (ANS) have been studied extensively (Waterhouse & Campbell, 2014). The ANS, which is divided into sympathetic and parasympathetic branches, handles an individual's unconscious reactions, such as maintaining homeostasis and cardiac responses to outside stressors. The sympathetic nervous system is often associated with the "fight-or-flight" response. Stressful situations result in physiological changes such as increased heart rate and blood pressure or increased respiration rate. The parasympathetic nervous system counterbalances the sympathetic nervous system by returning the body to a calm state. As described by the neurovisceral integration model (Nikolin et al., 2017), the sympathetic and parasympathetic nervous systems track activity in the prefrontal cortex.

One of the most commonly used physiological measures that can be used to infer cognitive load is respiratory sinus arrhythmia (RSA), which refers to the respiration-driven speeding and slowing of the heart (Shaffer & Ginsberg, 2017). A healthy heart is not a metronome; rather, there is variation in the time intervals between successive heart beats, known as heart rate variability (HRV). This variation between inter-beat intervals is constantly changing, which allows the cardiovascular system to rapidly adjust to sudden physical and psychological challenges to homeostasis. HRV indexes neurocardiac function and is generated by heart-brain interactions and ANS processes. Different frequency bands can be extracted from the HRV signal, including the high-frequency band, which ranges from 0.15 to 0.4 Hz. This is also referred to as the respiratory band, because it corresponds to the heart rate variations related to the respiratory cycle (i.e., RSA). Unlike heart rate, which is determined by both sympathetic and parasympathetic activity, RSA is a relatively pure index of parasympathetic control (Malik et al., 1996; Berntson et al., 1997).

A large number of studies have investigated RSA responses induced by mental workload tasks (e.g., Aasman, Mulder, & Mulder, 1987; Tattersall & Hockey, 1995; Wilson, 2002). Across both laboratory and field studies, increased cognitive demand has been shown to be highly associated with patterns of changes in heart rate. As cognitive load increases, RSA *decreases*. Lower RSA is also associated with decreased cognitive performance (Elliot, Payen, Brisswalter, & Cury, & Thayer, 2011). RSA can be used to reliably differentiate between an individual in a passive, resting state and an active state under mental load (Soga, Miyake, & Wada, 2007; Henelius, Hirvonen, Holm, Korpela, & Muller, 2009; Riener, Ferscha, & Aly, 2009; Reimer & Mehler, 2011; Taelman, Vandeput, Vlemincx, Spaepen, & Huffel, 2011). Throughout this dissertation, I assess fluctuations in RSA to infer potential changes in cognitive load. I measure RSA though Root Mean Square of the Successive Differences (RMSSD), which is the primary time-domain measure used to estimate the vagally mediated changes reflected in heart rate variability (Shaffer, McCraty, & Zerr, 2014). RMSSD has been shown to track cognitive load and provides detailed temporal resolution (Thayer & Lane, 2009).

While there have been decades of research showing associations between parasympathetic activity and cognitive load, it is important to note that RSA is not a one-to-one read-out of cognitive load, nor is it the only way to assess a person's mental workload. Lower parasympathetic activity has not only been shown to be associated with increased cognitive load and mental effort (Börger et al., 1999), but also tracks increased focused attention (Jönsson, 2007), and increased state anxiety and emotional strain (Nickel & Nachreiner, 2003), among other cognitive/emotional states.

In paradigms like the Trier Social Stress Test (Kirschbaum et al., 1993), which is designed to elicit a strong emotional response, participants' stress is so strong it washes out any effects of cognitive load on heart rate variability. In the current study, children could have experienced stress from having multiple cameras in the room and the nature of the math task and experimental setting. However, we made efforts to minimize stress by explaining during informed consent that the cameras were only there so we could go back later and remember what happened. Also, the experimenter never directly evaluated the children or gave them feedback on their performance. Thus, it is more likely that our parasympathetic measure is not simply reflecting differences in children's stress throughout the experiment beyond potential anxiety elicited from doing math. Given the robustness of previous demonstrations of RSA tracking cognitive load, we believe that interpreting this measure as a proxy for cognitive load in the current study is a reasonable interpretation.

I did not collect behavioral measures of cognitive load in the current experiment, but rather chose to use parasympathetic activity as a proxy for this construct because it allows for continuous and unobtrusive measurement of changes throughout the learning process. While typical behavioral studies manipulate the amount of cognitive load (e.g., by asking people to simultaneously perform two cognitive tasks at once), I wanted to measure naturally occurring levels of cognitive load without interfering with the math lesson. Compared to past gesture studies, adding a real-time, unobtrusive measure of cognitive load can enhance our understanding of differences between and within children over time as a function of whether or not they produce gestures, the kinds of gestures they produce, and their learning outcomes.

Producing gestures lightens cognitive load

Several studies have explored the link between gesturing and cognitive load. Goldin-Meadow and colleagues (2001) found that gesturing while explaining math problems, compared to not gesturing at all, reduces demands on a speaker's cognitive resources, thus freeing cognitive capacity to perform other tasks. Gesturing appears to confer cognitive benefits on working memory whether or not a speaker has mastered the task. The authors argue that gesture's ability to lighten cognitive load stems from its tightly integrated relationship with speech, in which the two modalities work together to convey meaning (Goldin-Meadow et al., 1993; McNeill, 1992). This idea builds off of a large body of research showing that gesture not only benefits listeners' comprehension, but also provides cognitive benefits for speakers themselves. Producing gesture may lighten a speaker's burden by priming access to a temporarily inaccessible lexical item and thus facilitating the processing of speech (Rauscher, Krauss, & Chen, 1996). Gesture production could also facilitate the link between the words a speaker utters and the world that those words map onto, as gesture comprehension has been shown to do (Glenberg & Robertson, 1999). Additionally, gesturing could help speakers organize information, especially spatial information, for the act of speaking and thus facilitate conceptualization of a message (Alibali, Kita, & Young, 2000).

Cognitive load and gesture-speech mismatch

Wagner, Goldin-Meadow, and Nusbaum (2004) found that gesture-speech mismatches and non-mismatches may have different effects on cognitive load (see also Ping & Goldin-Meadow, 2010). Participants remembered significantly more items (both verbal and visuospatial) when their gestures matched their speech than when their gestures did not match their speech. This aligns with Goldin-Meadow and colleagues' (1993) hypothesis that gesture-speech mismatches take up more working memory capacity than gesture-speech matches, since there are two messages being conveyed simultaneously (see also Nusbaum & Schwab, 1986). When gesture and speech covey the same information they may be able to reinforce one another and share some of the representational load, thereby easing a speaker's cognitive burden. Their findings suggest that the mere act of moving one's hand is not responsible for gesture's ability to reduce the load on working memory; rather the propositional content of the gestures (i.e., their meaning) seems to play an important role. In a mismatch, gesture conveys a message that is not easily integrated with the message conveyed in speech, so it is difficult for gesture to provide an overarching framework for its accompanying speech. In a match, gesture conveys the same meaning as speech (albeit from a different perspective), and thus can provide a framework that complements and organizes speech, thereby lightening the burden on working memory.

Goldin-Meadow, Nusbaum, Garber, & Church (1993) hypothesized that the simultaneous consideration of more than one strategy leads to uncertainty, which then provides the impetus for transition in the acquisition of concepts. They reasoned that, if a child recognizes, either explicitly or implicitly, that the information in her gestures conflicts with her accompanying speech, she might be compelled to reorganize her thinking to resolve the conflict. They provided evidence that mismatchers spontaneously entertain more than one strategy for solving a single problem by having children do a word recall task while solving a math task. While all children solved the math task incorrectly, children who had produced different strategies in speech and gesture while explaining the math problems performed worse on the word recall task than children who produced a single strategy. They argued that this impaired performance was due to mismatchers activating multiple strategies at once while solving the math problems, which increased their cognitive load, hence leaving less capacity available for rehearsing the words.

Prior work supports the theory that more working memory is required when multiple strategies are active simultaneously, compared to when a single strategy is activated. Conceptual representations under cognitive control are activated whenever people are asked to solve problems, recall problems, learn concepts, or understand language (Posner, 1978; Shiffrin, 1976). Operating these active control processes requires some form of cognitive capacity (e.g., Shiffrin, 1976; Navon & Gopher, 1979) and can limit the availability of working memory for other cognitive processes (Baddeley, 1986; Logan, 1979). There are increased demands on cognitive capacity whenever there are alternative hypotheses or interpretations for a particular cognitive process (Nusbaum & Schwab, 1986). An example from speech perception is when one acoustic cue can signal several different phonemes. Recognizing such a cue requires more capacity than recognizing a cue for which only a single interpretation exists. Similarly, if more than one strategy or solution is possible when solving a problem, evaluating the multiple solutions should require more capacity than evaluating a single strategy for a different problem (Goldin-Meadow et al., 1993)

Goldin-Meadow and colleagues (1993) suggest a potential cost to being in a state of transition. Their findings suggest that mismatchers, who are in transition with respect to the concept of mathematical equivalence, expend more cognitive effort when solving equivalence problems than non-mismatchers, and as a result are less successful at performing a simultaneous word-recall task. They hypothesize that this increased cognitive cost arises because the mismatchers activate, and maintain in working memory, both of the notions found in their mismatched explanations when they solve each of the problems. Hence, cognitive load and working memory capacity appear to play a key role in the transitional state and receptiveness to instruction. While increased cognitive load may seem like an adverse state, it could also be a motivating factor to learn a new concept, in order to resolve internal conflict and the heightened mental workload.

A combination of mechanisms could likely be contributing to the phenomenon of mismatchers being more likely to learn. For example, Perry, Church, and Goldin-Meadow (1998) suggest that both knowledge and conflict characterize the transitional state. They acknowledge that level of knowledge, indexed by whether a child's predominant explanation expresses equivalence or nonequivalence, is important to consider along with the stability of the child's knowledge, indexed by whether gesture and speech match or mismatch. Evidence suggests that mismatchers do not differ from non-mismatchers in terms of level of explicit knowledge expressed in speech (both children give incorrect, nonequivalence explanations), but do differ in amount of conflict or stability (mismatchers are more unstable) (Goldin-Meadow, Alibali, & Church, 1993). Hence, it is important to look at baseline differences in knowledge in addition to changes in knowledge over the course of learning. In addition to using behavioral measures such as gesture-speech mismatch and solutions on problems to assess transitions in knowledge, physiological markers can also reveal more subtle changes in cognitive processing over time.

The current work

This dissertation extends previous work on spontaneous gesture-speech mismatch and instructed gesture manipulations by adding a parasympathetic measure of cognitive load to add to our understanding of gesture's role in expressing and changing mathematical knowledge. In four chapters, I address separate, though related, research questions about gesture, cognitive load, and learning through a single experiment that included multiple assessments of knowledge before and after a math lesson.

I chose to focus on the concept of mathematical equivalence for several reasons. From a pragmatic standpoint, the math equivalence training paradigm has been used many times in past gesture studies and has been repeatedly shown to elicit strategies in speech and gesture that already have a well-defined coding scheme. We can easily compare our proportion of mismatchers and non-mismatchers and their learning outcomes to previous studies using similar methods (e.g., Perry et al., 1988; Goldin-Meadow et al., 1993; Alibali & Goldin-Meadow, 1993; Garber, Alibali, & Goldin-Meadow, 1998; Cook & Goldin-Meadow, 2006; Broaders et al., 2007; Cook, Mitchell, & Goldin-Meadow, 2008; Goldin-Meadow, Cook, & Mitchell, 2009; Goldin-Meadow et al., 2012; Novack et al., 2014). From an applied perspective, understanding the concept of mathematical equivalence is foundational for more advanced mathematics, including pre-algebra (Knuth, Alibali, McNeil, Weinberg, & Stephens, 2005; Byrd et al., 2015). Elementary school students in the United States generally perform poorly on math equivalence problems (McNeil, 2007), and difficulties understanding the relational nature of the equals sign often persist into middle school (Knuth et al., 2005; Alibali et al., 2007; Booth & Davenport, 2013). Students often have the prerequisite arithmetic skills necessary to solve such problems, so it is important to examine deficits in conceptual knowledge as a possible explanation for their poor performance and the mechanisms underlying successful learning of this concept.

Overview

In Chapter 1, I examine spontaneous gesturing in relation to speech while children are explaining how they solved math problems. I ask whether there are parasympathetic differences between children who already understand math equivalence and children who do not know how to solve these problems. Beyond differences in explicit knowledge, I also look within non-knowers to see if parasympathetic activity tracks differences in implicit knowledge, as measured by the presence of gesture-speech mismatches. Are mismatches associated with greater cognitive load than non-mismatches, as was suggested by Wagner and colleagues (2004)? Does mismatching reflect a person-level characteristic of a child in a state of transition, or do children waver in and out of such a state depending on whether or not they are producing a mismatch in the moment?

In Chapter 2, I investigate the effects of spontaneous verses instructed gesture on cognitive load. Are there parasympathetic differences between children who do or do not spontaneously gesture while explaining how they solved math problems? Does this depend on whether or not they got those problems correct? Within children who spontaneously produce gestures, does their parasympathetic activity vary from problem to problem depending on whether or not they gesture while explaining a given solution? Finally, for children with differing levels of explicit knowledge of math equivalence, what happens when they are instructed to produce a specific gesture? Does instructed gesture lighten cognitive load compared to being instructed to only use a strategy in speech while solving problems?

In Chapter 3, I focus on the effects of gesturing on learning for children with varying levels of math anxiety, due to past research suggesting pivotal connections between math anxiety, cognitive load, and performance. I hypothesized that children who are under higher levels of cognitive load due to anxious thoughts about math would particularly benefit from gesture instruction given gesture's ability to lighten cognitive load.

In the final chapter, I use parasympathetic activity to better understand changes in knowledge over time. Can we use physiological activity to differentiate between children who learn how to solve math equivalence problems and children who appear to learn but do not maintain this knowledge over time? Are there differences between children who undergo a cognitive change and those whose knowledge (either correct or incorrect) stays stable throughout a math lesson? The four chapters all stem from a single experiment and are connected thematically by their reliance on parasympathetic activity as way to measure continuous changes in cognitive states without interrupting the learning process. By examining psychophysiological changes underlying a well-studied behavioral paradigm, I aim to increase our understanding of the role gesture plays in reflecting differences in knowledge and shaping learning.

METHODS

Participants

142 children between the ages of 7 and 10 (M = 8.12 years, SD = 0.79 years) were tested individually in the Psychology Department at the University of Chicago. Past studies using a similar mathematical equivalence paradigm focused on children in third and fourth grade, but we chose to also include second graders given our different population of children. Unlike previous work, which was primarily conducted in Chicago Public Schools, we conducted our experiment in our lab. Children whose parents are willing to bring them to a university after school or on a weekend to do a study about math likely differ from those who are taken from their classroom during the day to participate in a study. We wanted to include a slightly wider age range to account for children who might come from schools that teach mathematical equivalence as early as second grade (including the closest elementary school to our campus). Participants were recruited from the Greater Chicago area through a database maintained by developmental psychology labs at the university and through flyer advertisements posted throughout the neighborhood. We screened out children who had previously participated in a math equivalence experiment in the Goldin-Meadow lab. Four participants were unable to complete the research session due to behavioral issues and thus were excluded from all analyses. Two additional children were excluded due to scheduling errors (one participant had previously participated in the study and another was outside the age range for the study). Thus, 136 participants (69 female, 67 male) are included in the following analyses.

The children in our sample were racially and ethnically diverse (47.8% white, 29.4% black, 5.8% Asian, 13.2% mixed race, 3.7% unreported; 12.5% Hispanic, 83.1% not Hispanic, 4.4% unreported), as identified by a demographic questionnaire filled out by parents while waiting for their child to complete the study. Our sample was also socioeconomically diverse, based on reports of yearly household income (8.1% less than $20,000, 11.0% $20,000-$34,999, 5.1% $35,000-$49,000, 19.1% $50,000-$74,999, 11.0% $75,000-$99,999, 16.2% $100,000-$149,000, 21.3% more than $150,000, 8.1% unreported). Our sample was skewed toward highly educated parents: 0.01% of parents had less than a high school degree, 0.02% had a high school degree or GED; 14.0% had some college, 11.2% had an Associate's degree, 22.8% had a Bachelor's degree, 2.9% had some graduate training, 41.9% had a graduate degree, and 3.7% of parents did not report education levels.

Procedure and behavioral measures

The experimenter greeted each family outside the psychology building and brought them to a waiting room, where they received a brief introduction to the experiment and signed informed consent. The parents were given a questionnaire to fill out while they waited (see Appendix A), which included demographic questions about their child and family, as well as scales assessing the parent's own level of math anxiety (Betz, 1978) and theory of intelligence (Dweck, 2000).

Children were brought upstairs to the testing room by the experimenter, where they put on a t-shirt over their current clothing to maintain consistency in video recordings that might be used in future studies. The experimenter then placed a Zephyr Bioharness 3 belt around the child's chest. This wireless physiological monitoring system recorded the child's heart rate and respiration throughout the whole experimental session. The electrode portion of the elastic strap was first wetted with water in order to increase the cleanliness of the signal. The entire experimental session was video recorded for subsequent coding and analysis.

In order to get a physiological baseline, participants first stood for five minutes while watching a clip from BBC's Planet Earth Shallow Seas (Season 1, Episode 9). We chose a nature video as has been done in past studies to get a neutral baseline, but acknowledge that viewing nature could have an attention restoration effect (Berman, Jonides, & Kaplan, 2008) and perhaps wash out initial physiological differences between children. After the video clip ended, participants reported their current mood on a smiley face rating scale from 1 (very good) to 5 (very bad) ($M = 1.72$, $SD = 0.82$). While still standing, participants then watched a 10-second clip without sound of a person gesturing over two different sets of colored balls, for a separate question about individual differences in the perception of representational movement (Novack, Wakefield, & Goldin-Meadow, 2016). The experimenter asked participants to describe what happened in the scene as was done in a recently published study (Wakefield, Novack, & Goldin-Meadow, 2017)

Children next sat down at a table to begin the math portion of the experiment, which included several phases. The procedure and materials for pretest through posttest were identical to those used by Goldin-Meadow, Cook, and Mitchell (2009). Four video cameras recorded the math portion of the experiment for a separate question about subtle changes in movement and facial expressions over the course of learning (Mangelsdorf, Cook, & Goldin-Meadow, 2016). There was one camera on the ceiling, one behind the whiteboard capturing the child's face, one to the child's right side, and one over the child's right shoulder.

Written pretest

Using pencil-and-paper, participants solved six mathematical equivalence problems (see Appendix B for all of the problems used throughout the lesson). Half of the problems were in the form $a + b + c = \_\_ + c$ (e.g., $5 + 8 + 2 = \_\_ + 2$) and half were in the form $a + b + c = a + \_\_$

(e.g., 7 + 5 + 8 = 7 + __). Children were allowed to take as much time as they needed to solve the problems (M = 3 minutes 16 seconds, SD = 2 minutes, range = 25 seconds - 13 minutes 24 seconds) and to notify the experimenter when they were finished. We used two versions of the mathematical-equivalence test, as has been done in previous studies; if a child was given version A at the pretest, that child was given version B at the posttest, and vice versa.

Pretest explanation

After children finished solving the pretest, the experimenter wrote each of the problems on a whiteboard (onto a set template with equally spaced plus signs, equal sign, and blanks), along with the children's solutions and asked them to explain how they got their answers. While there were no explicit instructions to use their hands while explaining their solutions, 87% of children gestured spontaneously while speaking.

Instruction

In the next phase, a new experimenter, who was blind to the child's pretest performance, entered the room to teach each child a strategy for solving the problems (the first experimenter was gone from the testing room during the instruction and training phases). The first experimenter had erased the previous problem from the board to ensure that the second experimenter had no knowledge of the child's pretest performance. Across all three randomly assigned conditions, experimenter two taught the child to say "I want to make one side equal to the other side." In the "Correct Gesture" condition (n=48), the children accompanied those words with a grouping gesture (they placed a "V" hand under the a and b in the problem and then pointed at the blank space). In the "Incorrect Gesture" condition (n=37), they produced the same grouping gesture but pointed at incorrect addends on the left side of the equation (the b and c). In the “No Gesture” condition (n=51), children were taught the speech alone. There was an unequal number of participants across conditions because we wanted an equal number of non-knowers for later analyses and the proportion of non-knowers in each condition was slightly different. The experimenter demonstrated the strategy on three separate problems (with no solutions in the blank), only moving on to the next problem once the child successfully copied the full strategy. After each problem, the child was instructed to remember the words (and hand movements for the gesture conditions), because the experimenter was going to ask the child to produce them in the next part of the study. The problems during instruction were all in the form a + b + c = __ + c.

Training

After children learned the strategy, they solved six new problems on the whiteboard (all in the form a + b + c = __ + c), alternating with the experimenter verbally explaining six other problems with no accompanying movements. For each of the child’s problems, the child first produced the strategy that he or she was taught, then wrote his or her answer in the blank, and again repeated the strategy (see Appendix C for the full script used by the second experimenter in the instruction and training phases). After the last problem, the second experimenter left the room and the first experimenter returned to conduct the remainder of the study. Although the first experimenter was aware of children’s pretest performance, she was unaware of the child’s performance during training and immediately handed the child the posttest problems to solve on paper. Thus, there was little time in which the experimenter could have influenced the child’s performance on the written posttest.

Written posttest

Children returned to the table to solve six new problems with pencil-and-paper. Like the pretest, half of the problems were in the format on which the children were trained ("trained problems"; a + b + c = __ + c), and the other half moved the location of the blank ("near-transfer problems"; a + b + c = a + __), and hence required children to truly understand the concept of equivalence (insensitive to order), as opposed to simply using the strategy they were taught and always adding the first two numbers in each equation.

Posttest explanation

The experimenter then wrote children's posttest solutions on the whiteboard and the children explained how they got their answers while standing, just like they did for the pretest problems.

Written generalization test

Children answered one more set of problems, which required them to transfer what they learned to three new types of equivalence problems ("far-transfer problems"; see Appendix B). These included two problems with the blank on the right side of the equation but no more equal addends, two problems with the blank on the left side of the equation and equal addends, and two problems with the blank on the left side and no equal addends.

Additional measures

Following the math portion of the study, which lasted approximately 30 minutes, the experimenter turned off the three additional cameras and moved the primary camera to face the child, who stayed seated at a table next to the experimenter for the remainder of the experiment.

Immediately after finishing the generalization test, children answered questions about how confident and nervous they felt during each of the previous portions of the math task (Appendix D). Although children's retrospective memory of how they felt during each phase of the math task may not be accurate, we did not want to ask them during the math task in case it changed their behavior. Children also answered questions about their self-perceived competence in math and their affect towards math (Appendix E, Arens & Hasselhorn, 2015). The items and response options were read aloud to account for uneven reading abilities and speeds across participants.

Children's spatial working memory capacity was then tested using the Corsi block task (Corsi, 1972), in which the experimenter points to an increasing number of blocks in a certain order and children are instructed to point to the same blocks in the same order, or in the backwards order in the second part. The forward span task was always administered before the backward span task. For the backward span, children received a practice trial before starting the assessment trials. Each part ended once the child got two trials in a row incorrect. A composite of the number of correct trials across forward and backward tasks served as our spatial working memory measure.

Individual differences in interoceptive sensitivity were measured using a heartbeat perception task (Schandry, 1981), following the procedure developed for 6- to 11-year-old children by Koch and Pollatos (2014). After a 10-second practice trial, participants counted how many times their heart beat between hearing audio recordings saying "start" and "stop" and also reported their confidence on a scale from 0-100. They did this for three trials (15 seconds, 20 seconds, and 18 seconds), each separated by a 20-second break. Participants were instructed to not use any tricks like feeling their pulse or holding their breath.

Each child was next asked about their mindset towards the malleability of intelligence in math and in general (Dweck, 2000). Children were asked how much they agreed or disagreed with a series of statements, such as “Your intelligence is something about you that you can’t change very much.” The items and response options were read aloud to account for uneven reading abilities and speeds across participants.

Next, participants completed a forward and backward digit span task (Wechsler, 1991), which measured their verbal working memory capacity. A composite of the number of correct trials across forward and backward tasks served as our verbal working memory measure. The forward and backward digit span scores were combined because working memory is thought to be composed of memory processes measured by forward span as well as by executive function processes measured by backward span (Baddeley, 2000). The experimenter said a series of numbers aloud (at the rate of approximately one number per second) and the child repeated the numbers in the same order (or backwards order in the second portion). The forward span set size ranged from 2 to 9 items, whereas the backward span set size ranged from 2 to 8 items. The forward span task was always administered before the backward span task. For the backward span, children received a practice trial before starting the assessment trials. Each set size was assessed on two trials, and children began with the smallest set size of 2. Children who completed one or both trials at a particular set size correctly were given two additional trials at the next set size. The digit span task ended when children were incorrect on both trials of a given set size.

Finally, participants completed the Scale for Early Math Anxiety (Wu et al., 2012; Appendix F). They first saw math problems (which they read to themselves or asked the experimenter to read for them) and were asked to point to the face matching how nervous they would feel if they had to solve each math problem (children were not asked to solve the actual problems). Then each child was asked to imagine ten common scenarios involving math (e.g., "You are about to take a math test") and to report how nervous he or she would feel in each situation.

After the last task, the experimenter turned off the video camera, removed the physio belt and t-shirt, and let the child choose prizes from a bag of stickers, erasers, and miscellaneous toys. The experimenter and child then returned to the waiting room to debrief the parent and give $15 to compensate the family for their travel and time. The entire experimental session lasted approximately one hour and fifteen minutes.

Coding pretest and posttest explanation strategies

Children's explanations in speech and gesture were coded in terms of procedures used to arrive at a solution to the problem (see Perry et al., 1988 for details about the coding scheme). Two trained coders first transcribed children's speech from the videotape and coded the strategies without attending to gesture. 78% of children's verbal responses could be coded according to this scheme. On the second pass, the child's gesture was transcribed and the strategies expressed were coded without attending to speech. Movement of the hand during the explanation task was counted as a gesture if there was no obvious alternative purpose to this movement (such as fiddling with hair or folding the hands together). Gestures were described in terms of three parameters: hand shape, motion, and location in space. 72% of children's gestural responses could be coded according to this scheme. Speech or gesture was considered "uncodable" if no strategy was discernable (i.e., children indicated elements of the problem but did not combine the elements into any identified strategy). Coder agreement was 86% for strategies expressed in speech, and 75% for strategies expressed in gesture (N = 816).

Discrepancies between coders were solved by discussion. Table 1 displays examples of the most common explanations given in speech and gesture.

Table 1: Examples of children's explanations in speech and gesture for the problem 5 + 8 + 2 = __ + 2

Type of Procedure	Speech	Gesture
Incorrect procedures		
Add all the numbers	"I added the 5 plus 8 plus 2 plus 2 equals 17"	Point at 5, point at 8, point at left 2, point at right 2, point at solution
Add to the equal sign	"I added the 5 plus 8 plus 2 and got 15"	Point at 5, point at 8, point at left 2, point at solution
Carry	"They don't have another 8 like that so I put the 8 over there"	Point at 8, point at solution
Correct procedures		
Equalizer	"5 plus 8 plus 2 equals 15, so to make the other side equal 15 you need 13 more"	Sweep across 5, 8, and 2 on left side of the equation, point at equal sign, sweep across solution and 2 on right side of the equation
Grouping	"I added the 5 and the 8"	V-hand under 5 and 8, pause, point at solution
Equivalent addends	"I saw a 2 here and another 2 here."	Point at right 2, point at left 2
Equivalent addends plus grouping	"Since there was a 2 here and a 2 here, I added the 5 and the 8 and got 13"	Point at right 2, point at left 2, drop hand; V-hand under 5 and 8, pause, point at solution
Add-subtract	"I added 5 plus 8 plus 2 and that equals 15 so then I had to subtract the 2 over here and I got 13 for the answer"	Point at 5, point at 8, point at left 2, pause, pull hand down under right 2, point at solution

Note. The children either put the correct solution (13, in this example) in the blank or gave one of a number of incorrect solutions generated by different procedures, such as 17 (add all the numbers), 15 (add to the equal sign), or 8 (carry).

In the final step, the coders compared the speech code and the gesture code for each explanation to determine whether the gestured and spoken strategies matched. If the strategy conveyed in gesture was the same as the strategy conveyed in speech, then the explanation was categorized as a "match." We classified an explanation as a "mismatch" when the information conveyed by gesture was not conveyed in the accompanying speech. Table 2 presents examples of common gesture-speech mismatches.

Table 2: Types of gesture-speech explanations for the problem 5 + 8 + 2 = __ + 2

Type of explanation	**Speech**	**Gesture**
Gesture-speech match speech incorrect, gesture incorrect	"I added 5 + 8 + 2 and I got 15" (Add-to-Equal)	Point to 5, to 8, to left 2 (Add-to-Equal)
Gesture-speech mismatch speech incorrect, gesture incorrect	"I added 5 + 8 + 2 and I got 15" (Add-to-Equal)	Point to 5, to 8, to left 2, to right 2 (Add-All)
Gesture-speech mismatch speech incorrect, gesture correct	"I added 5 + 8 + 2 and I got 15" (Add-to-Equal)	Sweep under the left side of the problem, sweep under the right side of the problem (Equalizer)
Gesture-speech mismatch speech correct, gesture incorrect	"I just added 5 + 8 so I put 13" (Grouping)	Point to 5, to 8, to left 2, to right 2 (Add-All)

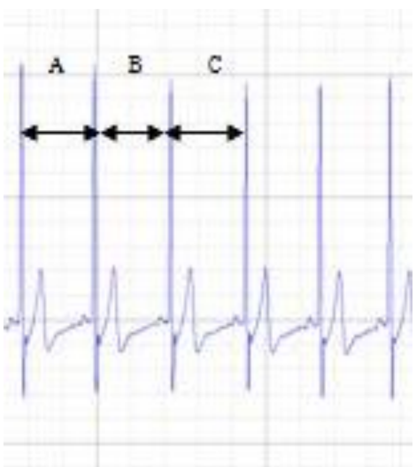
Physiological measures

Children's physiological responses were measured with a Zephyr BioHarness 3 bio-monitor, which was attached around each child's chest with an adjustable strap and was held in place with an additional strap diagonally across the chest. The monitoring belt, which was sewn tighter to fit children, consisted of three smart fabric sensors to acquire cardiac activity, breathing rate and skin temperature. The electrocardiogram (ECG) was obtained using the standard lead II configuration. The ECG data was sampled with 250 Hz. All ECG data were visually inspected, preprocessed, and analyzed using Mindware Software version 3.1.1.

Heart rate variability was derived by spectral analysis of the inter-beat interval series derived from the ECG, following previously specified procedures (Berntson et al., 1997). The inter-beat interval series was time sampled at 4 Hz (with interpolation) to yield an equal interval time series. This time series was detrended (second-order polynomial), end tapered, and submitted to a fast Fourier transformation. High frequency heart rate variability (HF HRV) spectral power was then integrated over the respiratory frequency band (0.2–0.50 Hz) to derive cardiovascular measures of parasympathetic cardiac control (RSA).

In the present work, I used the root mean square successive difference (RMSSD), one of a few time-domain tools used to assess RSA. The below image (Figure 1) shows R-R intervals labeled A (R-R_1), B (R-R_2), and C (R-R_3). In the below equation, N represents the number of R-R interval terms and R-R_i represents the interval between two neighboring R peaks. The RMSSD looks for the successive difference between the intervals, meaning A-B $\rightarrow (R\text{-}R)_1 - (R\text{-}R)_2$, B-C $\rightarrow (R\text{-}R)_2 - (R\text{-}R)_3$, and so forth.

Figure 1: Calculation of RMSSD



$$\text{RMSSD} = \sqrt{\frac{1}{N-1}\left(\sum_{i=1}^{N-1}\left((R-R)_{i+1}-(R-R)_i\right)^2\right)}$$

RMSSD is sensitive to high-frequency heart period fluctuations in the respiratory frequency range and has been used as an index of vagal cardiac control (Berntston, Lozano, & Chen, 2005). I choose to use RMSSD as my measure of parasympathetic activity because it can reflect meaningful changes in short segments of time. As we would expect, RMSSD was negatively correlated with heart rate (r= -.766) and positively correlated with RSA (r= .867) at baseline. There were no gender differences in baseline RMSSD (t(84.2) = -0.38, p = 0.706).

There was also no relationship between baseline RMSSD and age (in days) ($F(1,96) = 0.049$, $p = 0.825$, Adj. $R^2 = -0.010$).

For all analyses, I outputted RMSSD in 10-second segments and then averaged across each participant's 10-second segments for each period of interest. Ten participants were excluded from analyses of physiological data due to the ECG data being too messy to identify R peaks (often due to the belt coming off the skin), and five participants were excluded due to experimenter issues synchronizing the physiological data with timing from the videos. Two participants were also removed from the present analyses due to arrhythmias. For the remaining 119 participants, 37 outlier segments (across 36 participants) were removed for being greater or less than three standard deviations from the mean of other segments within a given period of interest for a given participant. I then looked for outliers across each participant's six pretest solutions, 10-second window before writing each of their six answers during the training portion of the study, 10-second window around writing each training answer, and 10-second window after writing the solution for each of the six training problems. There were no within-participant outliers for these periods of interest. Lastly, I looked for outliers (again ± 3 SD from the mean) across participants for each period of interest. This resulted in my removing one outlier for the baseline period, one for the written pretest, five pretest explanations, five before writing, five around writing, and five after writing.

CHAPTER ONE: PARASYMPATHETIC CORRELATES OF KNOWLEDGE STATES

As previously reviewed, looking at the relationship between the content expressed in people's gestures and in their speech can help us identify the stability of their current state of knowledge. In addition to looking at the occurrence of gesture-speech mismatches, can looking at parasympathetic activity help us identify a child's understanding of math equivalence? To address this question, I looked at parasympathetic correlates of both explicit knowledge, based on children's performance at pretest, and implicit knowledge, based on their frequency of mismatches. Regarding gesture-speech mismatch, I also ask whether the cognitive load associated with simultaneously entertaining two strategies at once is consistent over time within a person who produces mismatches, or whether it varies within children from problem to problem depending on whether they produce a mismatch on a given problem. In other words, is mismatching a phenomenon on a person or problem level? Finally, in this chapter, I ask whether parasympathetic correlates of gesture-speech mismatch relate to learning outcomes for mismatchers in my sample, given previous evidence that children who produce mismatches are more likely to learn than non-mismatchers.

Results and Discussion

Classification of pretest knowledge

Figure 1 shows the distribution of children's pretest scores. In addition to children who solved none of the pretest problems correctly ("non-knowers," n=79) and those who solved them all correctly ("knowers," n=31), there were also some children who got 1-5 pretest problems correct ("quasi-knowers," n=26). Given the primarily bi-modal distribution of pretest scores, I decided to compare knowers to non-knowers as discrete groups and excluded the quasi-knowers from all subsequent analyses, as has been done in previous studies using this paradigm (e.g., Perry et al., 1988; Goldin-Meadow et al., 2009; Novack et al., 2014).

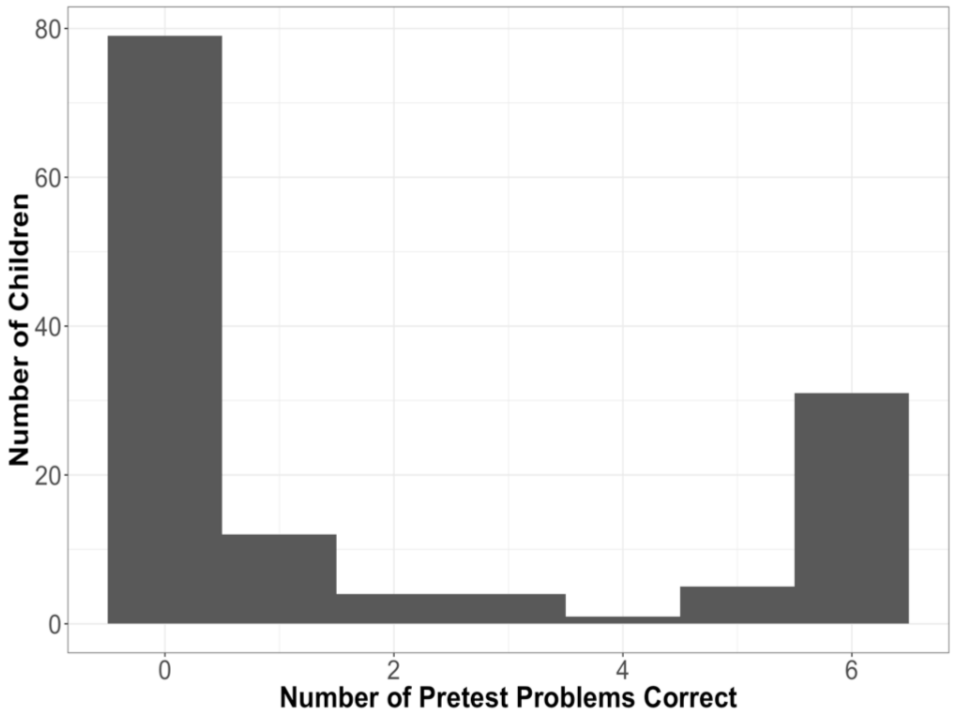


Figure 2: Distribution of Pretest Scores

Individual differences between knowers and non-knowers

Knowers were significantly older than non-knowers (t(46.019) = 2.256, p = 0.029, mean age for knowers = 8.454 years (SD = 0.861), mean age for non-knowers = 8.063 years (SD = 0.693), median grade for knowers: 4^{th}, median grade for non-knowers: 3^{rd}). Knowers also had significantly higher verbal working memory (t(52.078) = 4.089, p < 0.001, knowers M = 13.194 (SD = 2.880), non-knowers M = 10.158 (SD = 3.731)) and spatial working memory (t(62.872) = 3.441, p = 0.001, knowers M = 9.548 (SD = 3.161), non-knowers M = 7.139 (SD = 3.643)) than non-knowers. Knowers had a slightly lower mean math anxiety score than non-knowers (knowers M = 33.129 (SD = 11.372), non-knowers M = 36.589 (SD = 12.687)), but the difference did not reach statistical significance (t(60.877) = -1.388, p = 0.170). There were no significant gender differences between knowers and non-knowers ($\chi^2 = 0.936$, $p = 0.333$). For the knowers, 42% were female, compared to 54% of non-knowers. Median yearly household income for knowers was between $100,000 and $149,999, and median income for non-knowers was between $50,000 and $74,999, a significant difference ($t(53.564) = 3.237$, $p = 0.002$). Given these significant differences in age, spatial/verbal working memory, and income, I controlled for these variables in subsequent analyses.

Parasympathetic differences in explicit knowledge

Controlling for age, spatial/verbal working memory, and income, there was no difference between knowledge groups in baseline parasympathetic activity (RMSSD), outputted in 10 second segments across the 4 minute and 20 second baseline Planet Earth video ($p = 0.854$ $\beta = -0.788$). There were also no differences between knowers and non-knowers in baseline affect, self-reported right after viewing the Planet Earth video ($p = 0.514$, $\beta = 0.131$). In addition, there were no differences between knowledge groups in parasympathetic activity (RMSSD) while children solved the written pretest ($p = 0.589$, $\beta = 3.789$).

If knowers experience less cognitive load while explaining their pretest solutions due to already understanding mathematical equivalence, this could be reflected in greater parasympathetic activity compared to non-knowers who are unable to solve the math problems. However, I found no significant difference between knowers ($n = 28$) and non-knowers ($n = 71$) in average parasympathetic activity (RMSSD) during their pretest explanations, controlling for income, age, and spatial/verbal working memory in a multiple linear regression ($p = 0.182$, $\beta = -4.706$). Descriptively, knowers had slightly greater parasympathetic activity ($M = 33.762$) than non-knowers (M = 29.436). Controlling for each individual's baseline RMSSD in the regression revealed a similar result ($p = 0.112$, $\beta = -3.560$).

Interestingly, not all knowers reported being "very confident" in their pretest answers, so I looked to see whether confidence was related to parasympathetic activity while explaining pretest answers. I predicted that the more confident children are, the less cognitive load and emotional strain they should be experiencing, and hence they should have greater parasympathetic activity than children who report being less confident. Figure 2 shows the relationship between confidence and RMSSD for knowers and non-knowers. A linear regression (controlling for income, age, and working memory) revealed a significant main effect of knowledge group ($p = 0.034$, $\beta = -18.184$), a significant main effect of confidence ($p = 0.013$, $\beta = -8.284$), and a significant interaction of knowledge group and confidence ($p = 0.027$, $\beta = 8.050$). Adding baseline RMSSD into this regression weakens these effects (main effect of knowledge group: $p = 0.052$, main effect of confidence: $p = 0.158$, interaction: $p = 0.191$), so this relationship, if one truly exists, may be weak.

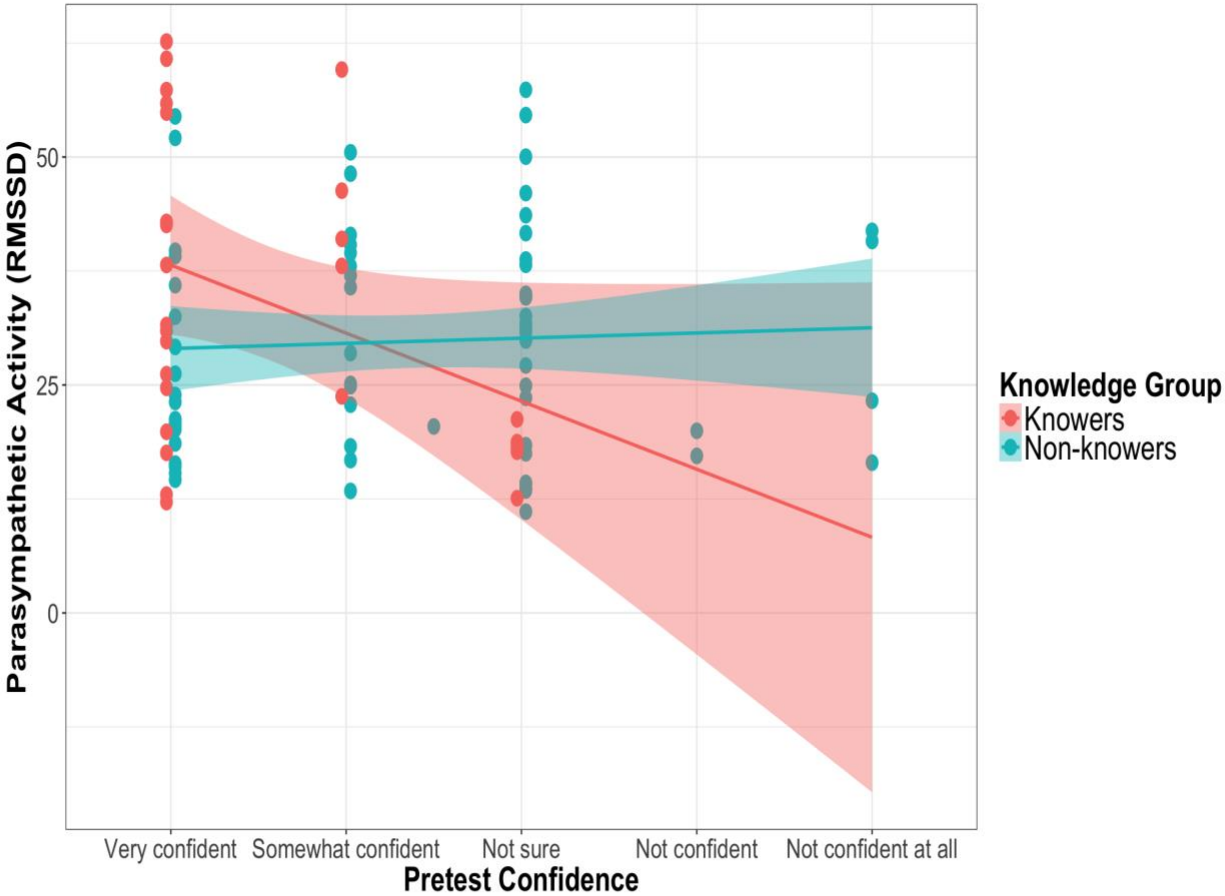


Figure 3: Relationship between children's self-reported confidence in pretest answers and their parasympathetic activity (RMSSD) while explaining their pretest answers

As discussed in the introduction, RMSSD is not just associated with cognitive variables such as mental workload and effort, but can also track feelings such as anxiety. I thus looked to see if children's nervousness while explaining the pretest solutions (reported right after the math task completed) was related to parasympathetic activity. Controlling for age, working memory, and income, there was a trending main effect of nervousness on RMSSD ($p = 0.096$, $\beta = 5.879$), no main effect of knowledge group ($p = 0.352$, $\beta = 7.265$), and a trending interaction between nervousness and knowledge group ($p = 0.079$, $\beta = -6.834$). Interestingly, there was no relationship between parasympathetic activity during pretest explanations and children's score on the Scale for Early Math Anxiety (Figure 4; main effect of knowledge group: $p = 0.433$, $\beta = -7.955$, main effect of math anxiety: $p = 0.547$, $\beta = -0.146$, interaction: $p = 0.750$, $\beta = 0.088$).

Although individual's general math anxiety score was significantly associated with their rating of nervousness during the pretest explanations ($p < 0.001$), only nervousness seems to track with RMSSD.

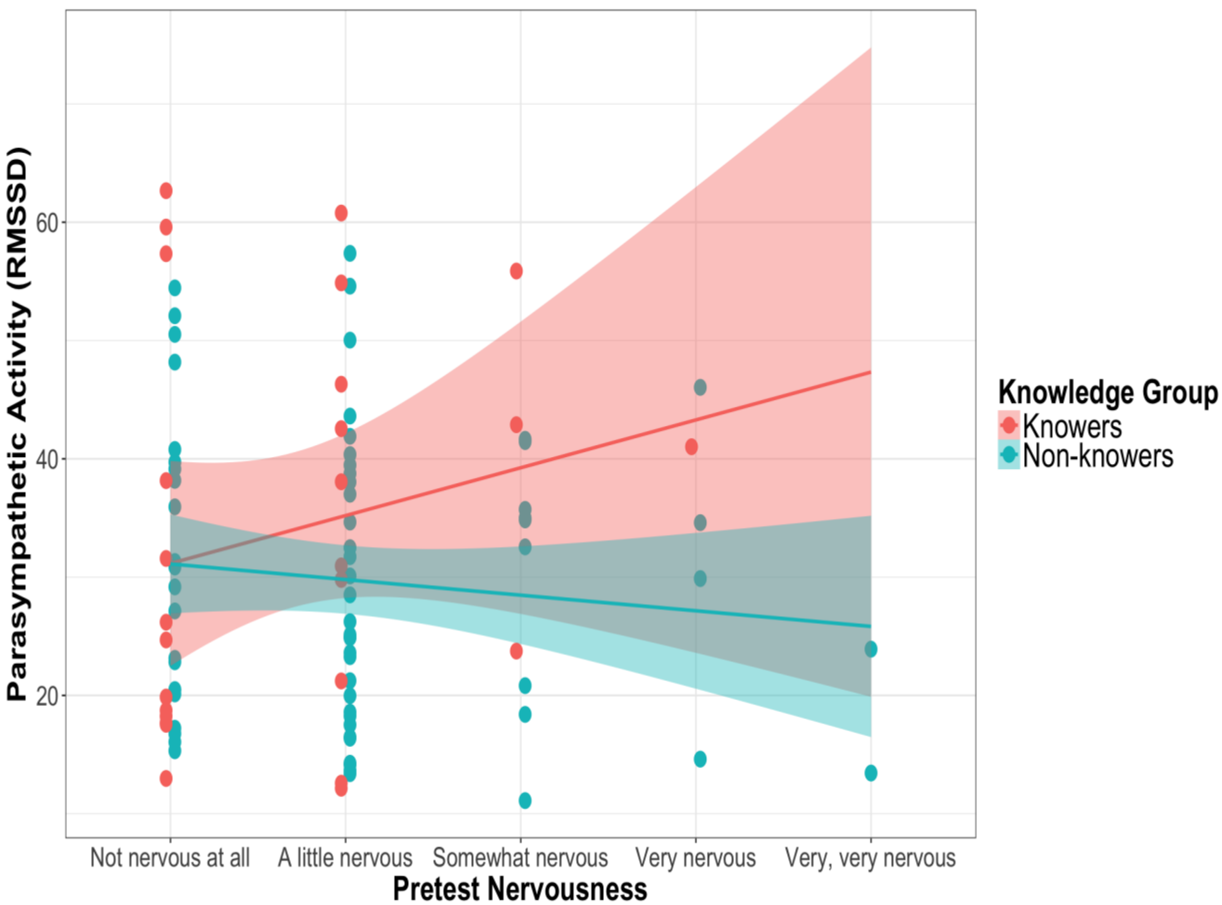


Figure 4: Relationship between nervousness and parasympathetic activity during pretest explanations for knowers and non-knowers

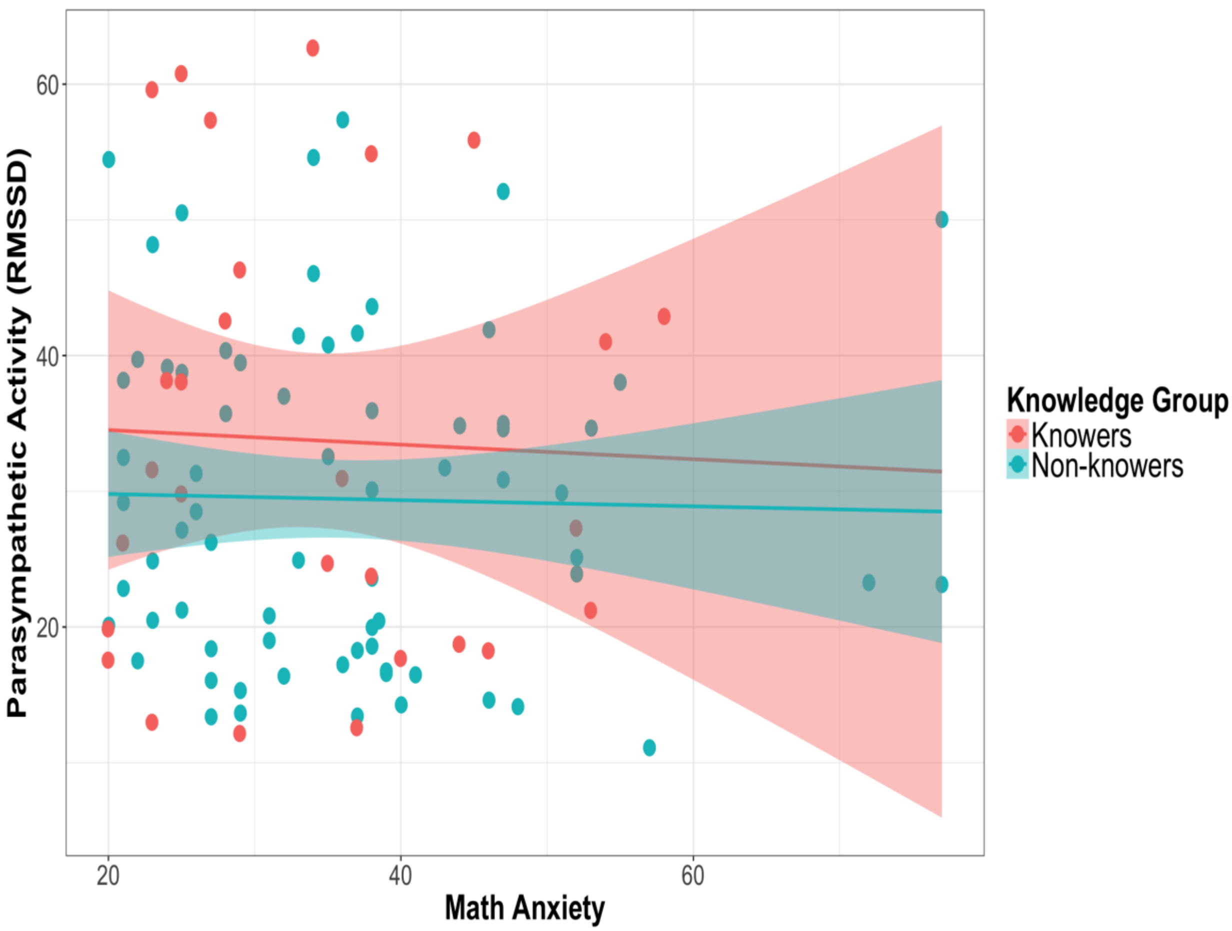


Figure 5: Relationship between math anxiety scores and parasympathetic activity while explaining pretest solutions for knowers and non-knowers

Parasympathetic differences in implicit knowledge

As reviewed earlier, children who convey different information in their speech and gesture ("mismatchers") are in a state of cognitive instability, compared to children who do not produce gesture-speech mismatches. Is this cognitive instability detectable on a physiological level? Past studies typically classify children as mismatchers or non-mismatchers, suggesting a binary person-level characteristic. However, children may have varying levels of cognitive instability that is reflected in varying numbers of mismatches.

I first looked at whether there were differences in parasympathetic activity between children as a function of how many mismatches they produced during their pretest explanations.

Baseline RMSSD while watching Planet Earth was not predictive of number of mismatches children produced while explaining their pretest math solutions, controlling for knowledge group, income, age, and working memory ($p = 0.215$, $\beta = -1.283$), so I used raw RMSSD scores (rather than change from baseline scores) for all mismatch analyses. If the simultaneous activation of two strategies increases cognitive load, one might predict that the more often such activation occurs (especially if a child entertains more than two strategies across the six problems), the lower the RMSSD.

Indeed, there appears to be a negative relationship (see Figure 5) between number of mismatches and parasympathetic activity for both knowers ($r = -0.336$) and non-knowers ($r= -0.166$). A regression on all participants, controlling for knowledge group, income, age, and working memory, revealed a significant negative relationship between number of mismatches and parasympathetic activity ($p = 0.038$, $\beta = -1.757$, Adj. $R2 = 0.027$). Interpreting parasympathetic activity as a measure of cognitive load, this negative relationship suggests that the more mismatches an individual produces, the greater his or her cognitive load, which aligns with Wagner, Goldin-Meadow, and Nusbaum's 2004 finding. However, adding baseline RMSSD into this regression reveals an only trending significance ($p = 0.090$, $\beta = -0.932$, Adj. $R2=0.580$), so the strength of the relationship may be weak.

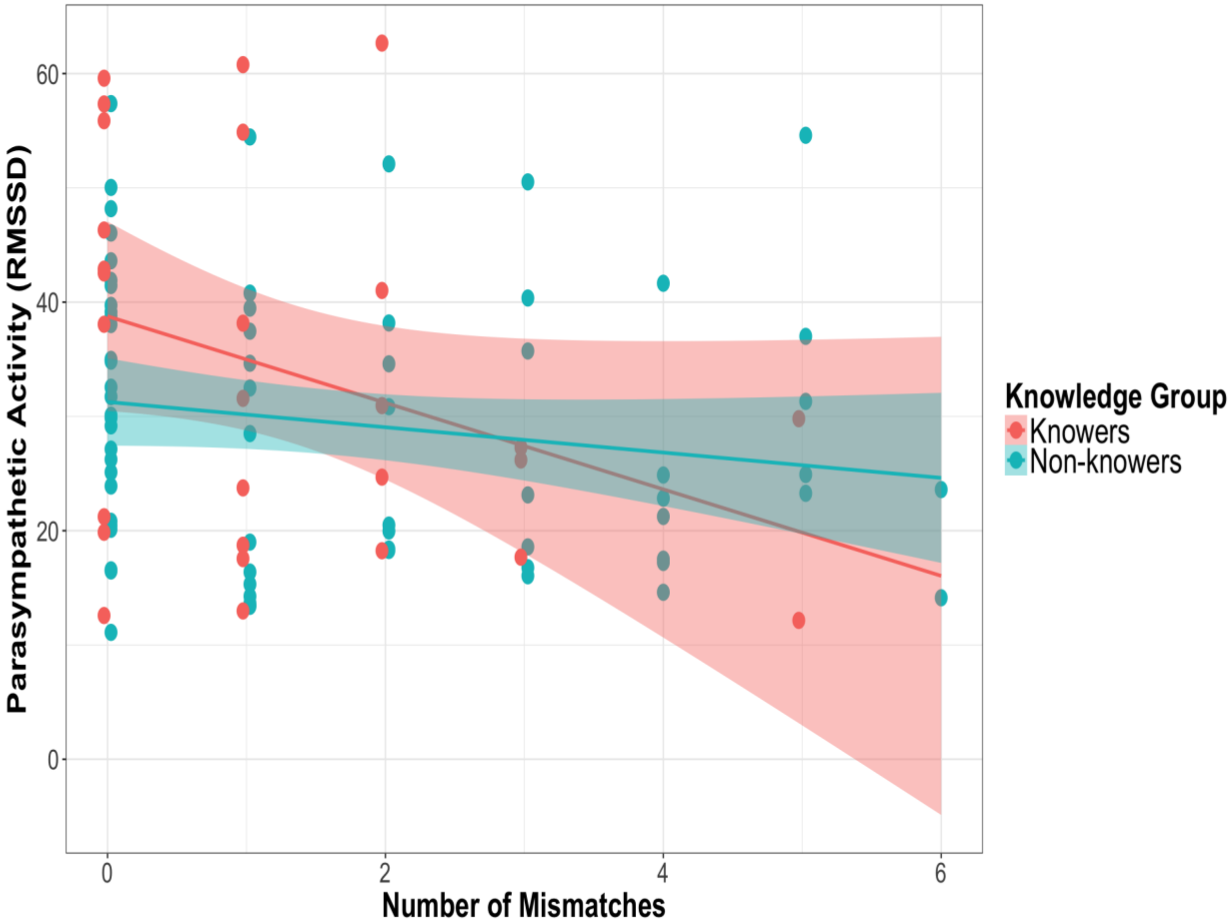


Figure 6: Parasympathetic activity of knowers and non-knowers based on each individual's number of pretest explanation trials containing a gesture-speech mismatch

An alternative explanation for the link between mismatch and RMSSD could be that the more mismatches a child produces, the greater emotional strain he or she is experiencing (at least for non-knowers). Such emotional disturbance or internal conflict could provide the impetus to learn the mathematical concept in order to reduce a feeling of unease. To investigate whether RMSSD should be interpreted in such a way, I looked at the relation between self-reported feelings of nervousness during the pretest explanations and number of mismatches produced (Figure 6). As you can see, there was no relationship between number of mismatches and nervousness ($p > 0.05$). This suggests that mismatching may be less associated with feelings of emotional unease, and more associated with cognitive variables.

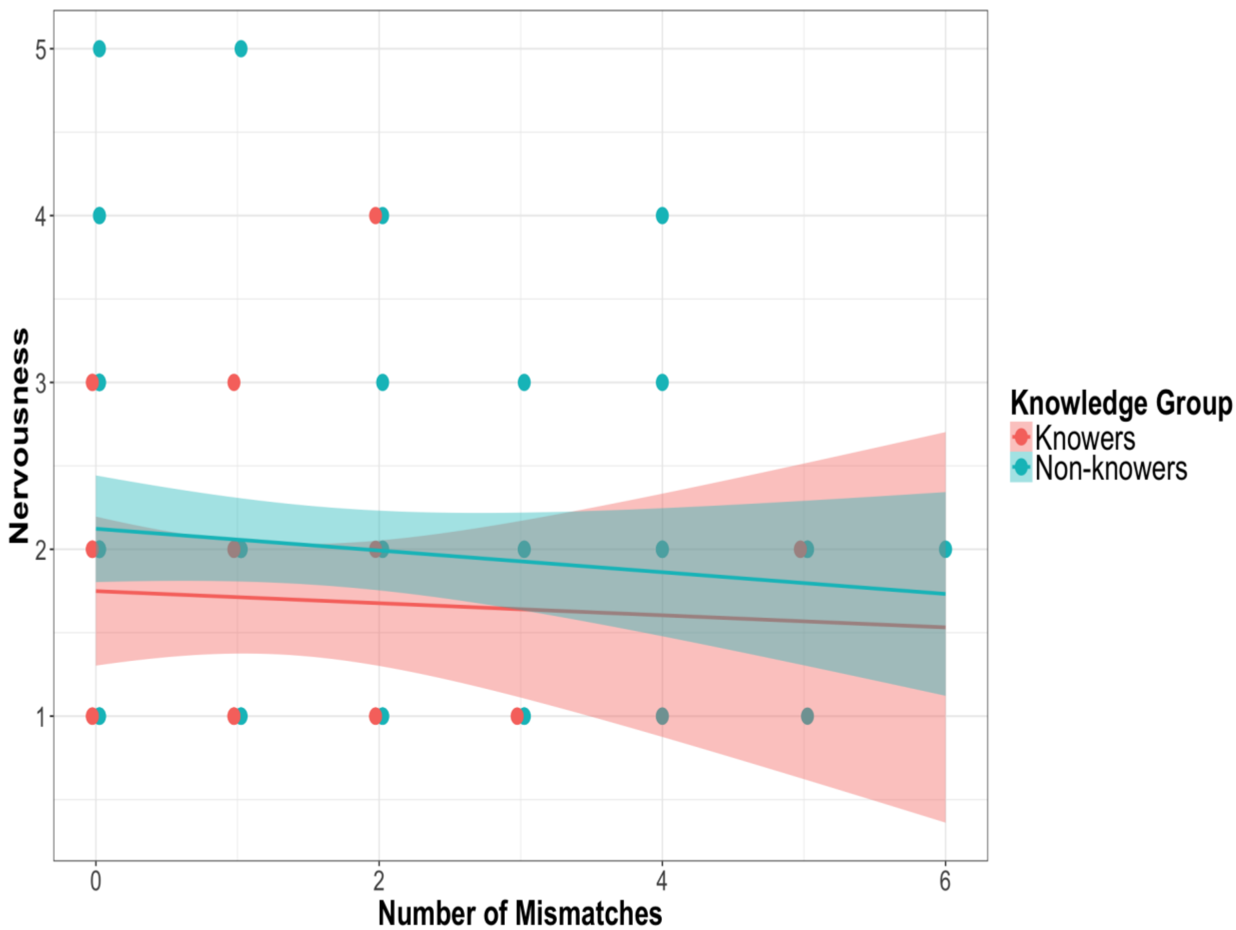


Figure 7: Relationship between nervousness during pretest explanations and number of mismatches

My next question was whether there are differences *within* children who produced between one and five mismatches on problems on which they mismatched vs. did not mismatch. As you can see in Figure 7, there was no difference in parasympathetic activity within mismatchers on trials on which they produced a mismatch vs. a non-mismatch, controlling for knowledge group, income, age, working memory, and baseline RMSSD ($p = 0.863$, $\beta = 0.283$). There was also no difference within mismatch problems on which the strategy expressed in a non-knower mismatcher's gesture was correct vs. incorrect ($p = 0.237$, $\beta = -3.590$), controlling for income, age, working memory, and baseline RMSSD. In addition, there were no parasympathetic differences within mismatchers before and after they produced their first mismatch (p = 0.854, β = -0.767), suggesting that mismatches are reflecting a child's existing knowledge of the concept, rather than creating new knowledge through the act of producing a mismatch. The phenomenon of gesture-speech mismatch appears to occur at the level of the person, rather than the problem.

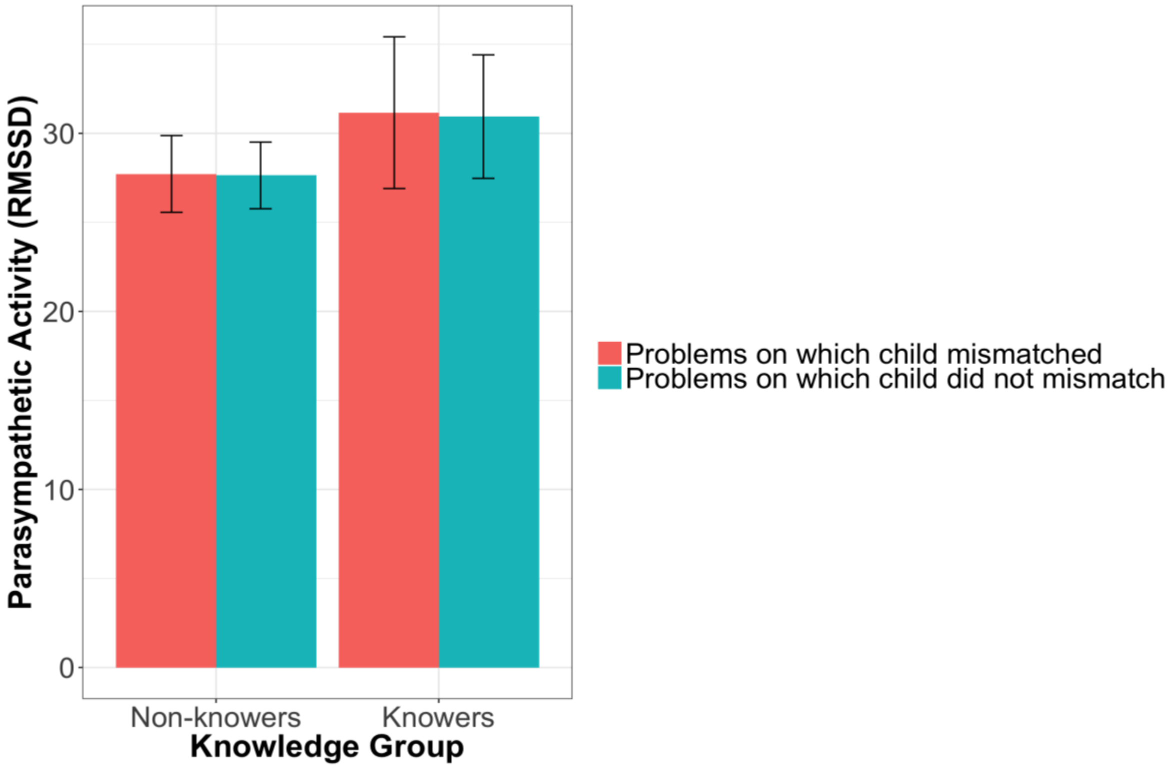


Figure 8: Parasympathetic activity on a problem level within children who produced at least one mismatch and at least one non-mismatch

Mismatch and learning

Do the differences in parasympathetic activity across non-knowers with varying numbers of mismatches relate to their learning? As reviewed earlier, mismatchers have been shown to be more receptive to instruction in a math equivalence lesson, so I first looked to see if that finding was replicated in the current sample. Figure 8 shows children's posttest performance (for children who got 0 pretest problems correct) as a function of number of mismatches produced during the pretest explanations. As you can see, there was not a significant relationship (p =

0.255, $\beta = 0.264$) between number of mismatches and posttest performance, controlling for income, age (or grade), working memory, and the lesson children received (taught a strategy in speech alone or speech + gesture). When adding individuals' parasympathetic activity during the baseline and pretest explanation phase into the regression, the relationship between number of mismatches and learning remains insignificant ($p = 0.295$, $\beta = 0.256$). It is unclear why I did not see the same relationship between mismatch and learning found in previous studies. One possibility, which I discuss in the next chapter, is the difference in the demographics of my sample compared to past research, which has been primarily conducted in schools.

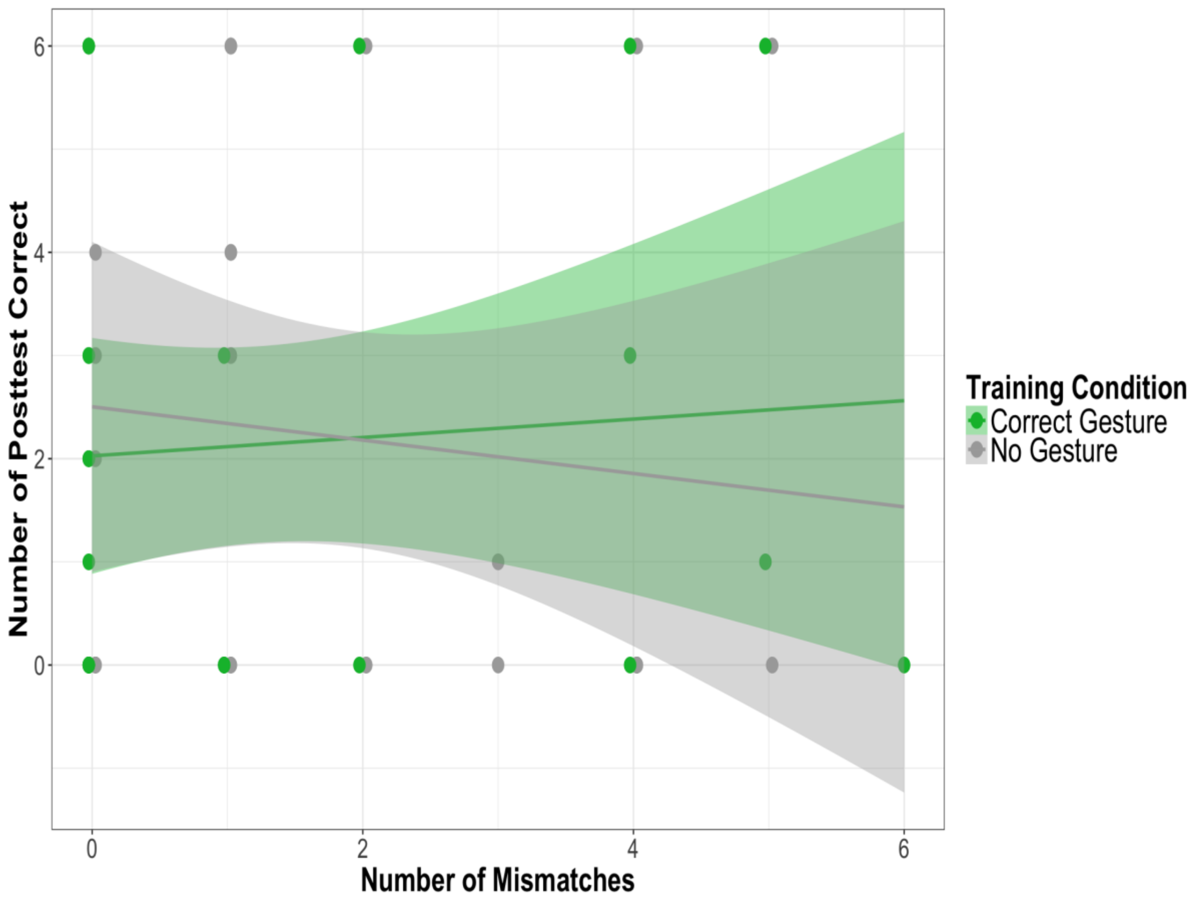


Figure 9: Number of non-knowers' pretest explanation trials containing a gesture-speech mismatch is not significantly related to their learning

CHAPTER TWO: PARASYMPATHETIC CORRELATES OF SPONTANEOUS AND INSTRUCTED GESTURE

This chapter uses parasympathetic activity (RMSSD) as a measurement of cognitive load to investigate previous claims that gesturing lightens cognitive load compared to not gesturing. While past studies have mainly explored this question in paradigms manipulating the presence of gesture, I compare instructed gesture to spontaneous gesture. In addition, like in chapter one, I ask whether differences in parasympathetic activity as a function of gesturing occurs at a person level (gesturers vs. non-gesturers) or problem level (within gesturers on problems on which they gesture vs. do not gesture).

Results and Discussion

Parasympathetic correlates of spontaneous gesturing

Given previous findings that gesturing lightens cognitive load, we predicted that children who gestured during the pretest explanations would have more parasympathetic activity than children who never gestured, since higher RMSSD is associated with lower cognitive load. An alternative hypothesis is that, since gesture is a means for reducing cognitive load, children who have no need to free up mental resources would not need to gesture. If this is the case, we would predict that children who do not gesture have greater parasympathetic activity (associated with less cognitive load) than children who spontaneously gesture while explaining their pretest explanations.

As in the first chapter, I began by continuously plotting parasympathetic activity as a function number of spontaneous gestures (Figure 9). There was a trending negative relationship ($p = 0.069$, $\beta = -1.093$), with more gestures being associated with lower parasympathetic activity, controlling for knowledge group (28 knowers and 71 non-knowers), income, age, and working memory. Spontaneous gesturing presents a difficulty in interpreting the relationship between gesture and cognitive load because we do not know the causal direction between choosing to gesture and cognitive load. Rather than the act of gesturing causing changes in cognitive load, differences in cognitive load may determine whether or not one gestures. It is possible that people who gesture have higher levels of cognitive load to begin with, compared to those who do not gesture, and produce gestures in order to reduce their mental workload. In contrast, people who never gesture, or produce fewer gestures, may have no need to lighten their cognitive load.

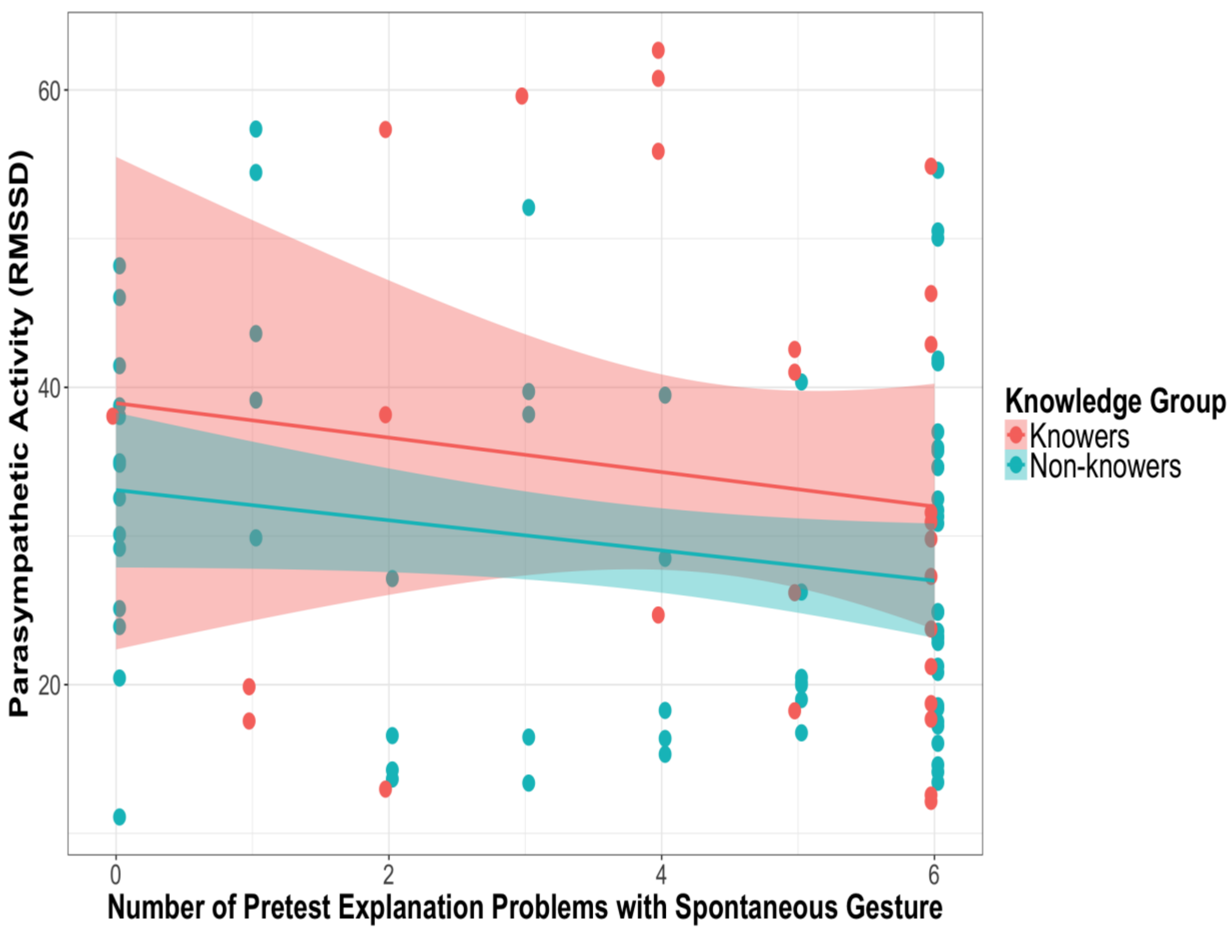


Figure 10: Parasympathetic activity during pretest explanations of knowers and non-knowers with varying levels of spontaneous gesture production

After looking at differences at the person-level among people with varying numbers of spontaneous gestures, I next looked within children who had a least one pretest explanation containing gesture and at least one explanation without gesture (13 knowers and 25 non-knowers) to see if there were differences in parasympathetic activity within each child when gesturing compared to not gesturing. As you can see in Figure 10, there were no parasympathetic differences within knowers or non-knowers based on whether or not the child gestured on a given problem, controlling for knowledge group, income, age, working memory, and baseline RMSSD ($p = 0.865$, $\beta = -0.411$). Again, looking at spontaneous gesture, it is not possible within the current paradigm to know if children chose to gesture on trials in which they were experiencing greater cognitive load. In order to address this issue, we need to manipulate gesture production.

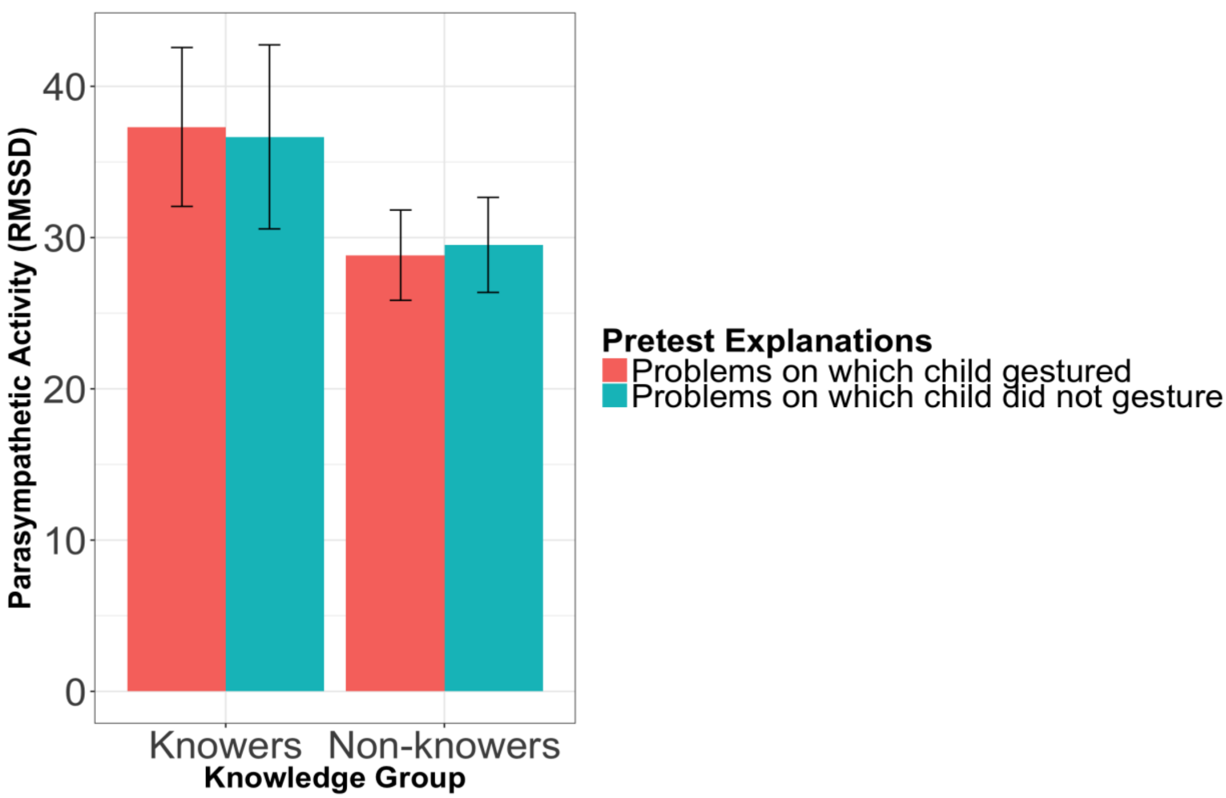


Figure 11: Parasympathetic activity within children who produced at least one pretest explanation containing spontaneous gesture and one explanation without gesture

Parasympathetic correlates of instructed gesturing

In this section, I looked at the parasympathetic activity of non-knowers (children who got none of the pretest problems correct) during the training problems on which they produced a strategy in either speech alone or speech+gesture before and after solving each problem. Figure 11 plots each participant's average RMSSD for 30 seconds windows around solving each of the six training problems as a function of the strategy they were asked to use. There was not a significant difference in parasympathetic activity for children who produced a gesture (while saying "I want to make one side equal to the other side") compared to the children who only said that speech, controlling for income, age, working memory, baseline RMSSD, and each individual's number of spontaneous gestures during pretest ($p = 0.938$, $\beta = -0.237$). There was also no evidence of gesturing lightening individuals' cognitive load from pretest to the first training problem, controlling for the same variables ($p = 0.283$, $\beta = 2.568$). Future work should look at more finely defined time windows before and during the first instructed gesture production to see if the act of producing an instructed gesture creates a change in parasympathetic activity.

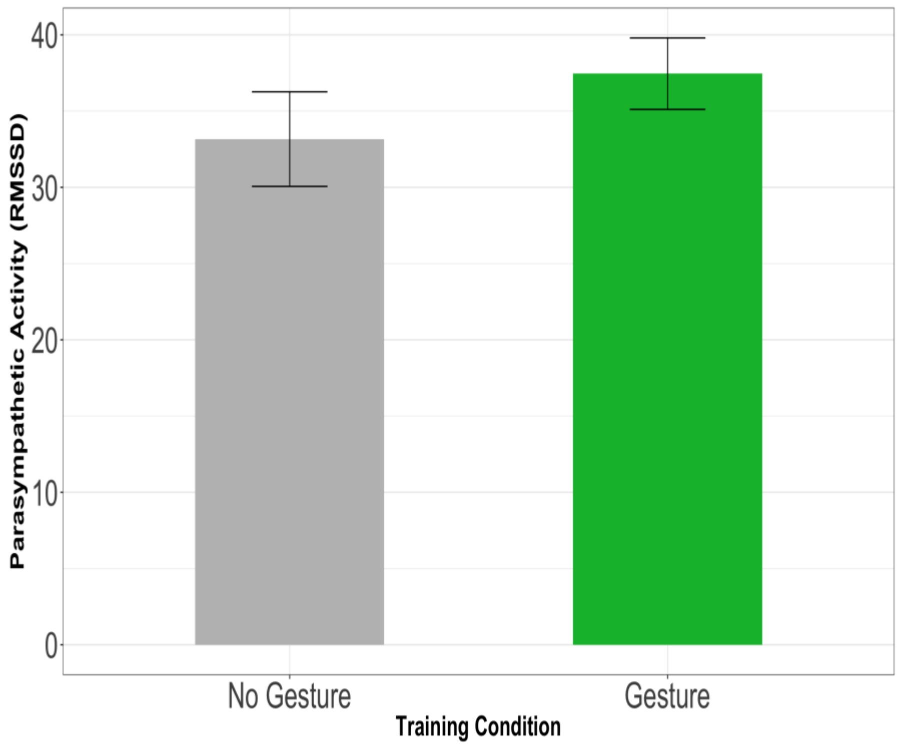


Figure 12: Mean parasympathetic activity for children in the no gesture condition compared to children in the gesture conditions (correct and incorrect combined). Bars show standard error of the mean

While not significant, descriptively, children who gestured had slightly higher parasympathetic activity on average, which aligns with past studies showing that instructed gesture lightens cognitive load compared to not gesturing. Given the possibility that movement of any form could potentially affect cognitive load, I looked at children in the training condition involving an incorrect grouping gesture (pointing to the wrong addends in the problem). As you can see in Figure 12, children who were asked to use this incorrect strategy descriptively had the highest parasympathetic activity while solving the training problems.

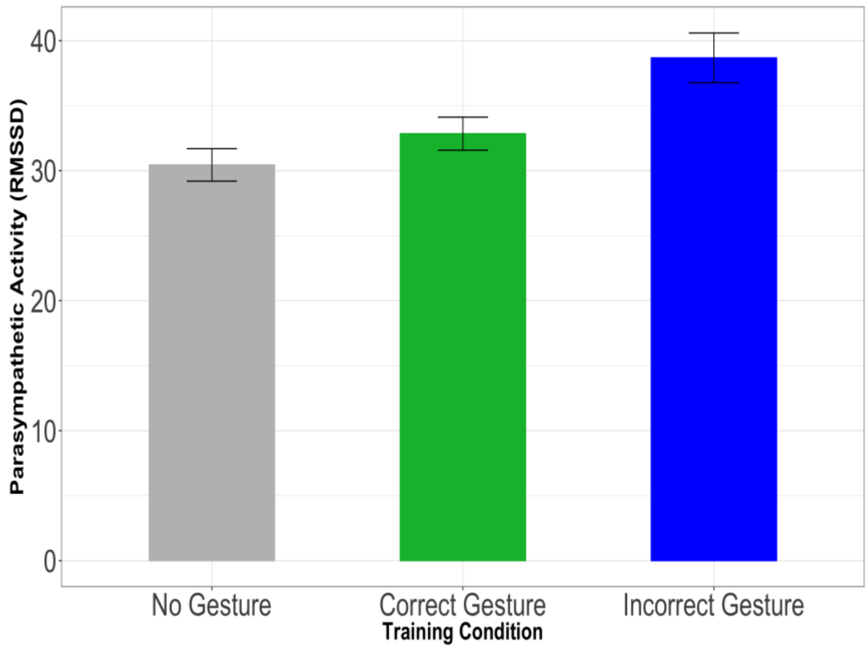


Figure 13: Average parasympathetic activity during training (windows around each solution) of children across the three training conditions

If movement is associated with lighter cognitive load than not moving, that alone may not account for learning outcomes, as children in the incorrect condition appear to perform slightly worse (descriptively) on the posttest than children in the correct gesture group (see Figure 13).

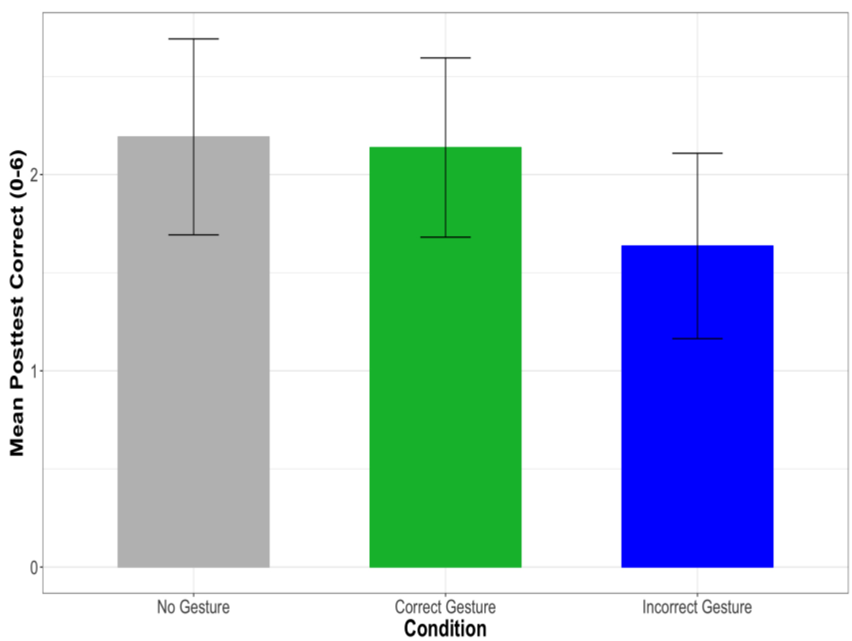


Figure 14: Learning outcomes for non-knowers based on their randomly assigned training condition

Individual differences in learning from gesture

Although I did not seek to directly replicate Goldin-Meadow, Cook, and Mitchell's (2009) finding comparing correct gesture, incorrect ("partially correct") gesture, and speech alone on learning, it is surprising that I saw no significant differences between training conditions in the current experiment. However, there are several major differences between my study and previous studies on the effects of gesture production on learning math equivalence. While most past studies were conducted in Chicago Public Schools, I ran participants in the lab at the University of Chicago, which is a very different testing environment. Also, the population of children willing to come to a university after school or on the weekends to participate in a math learning study is different from students who are taken out of their classrooms at school. In particular, my sample was less diverse socio-economically, racially, and in terms of percentage of children for whom English was a second-language (which has been shown in previous work by Church and colleagues to be an important individual difference variable in learning from gesture). English was the native language for 93% of our participants, so I couldn't look for language differences in learning for the current study.

Since the age range in my sample was wider than past math equivalence studies, I first looked to see if there was any relation between age and posttest performance across the three training conditions. As you can see in Figure 14, there was an overall main effect of age on posttest performance ($p = 0.043$, $\beta = 0.003$). There were no significant main effects or interactions when taking training condition into account. Descriptively, there appears to be positive relationship between age and learning for children in both gesture conditions.

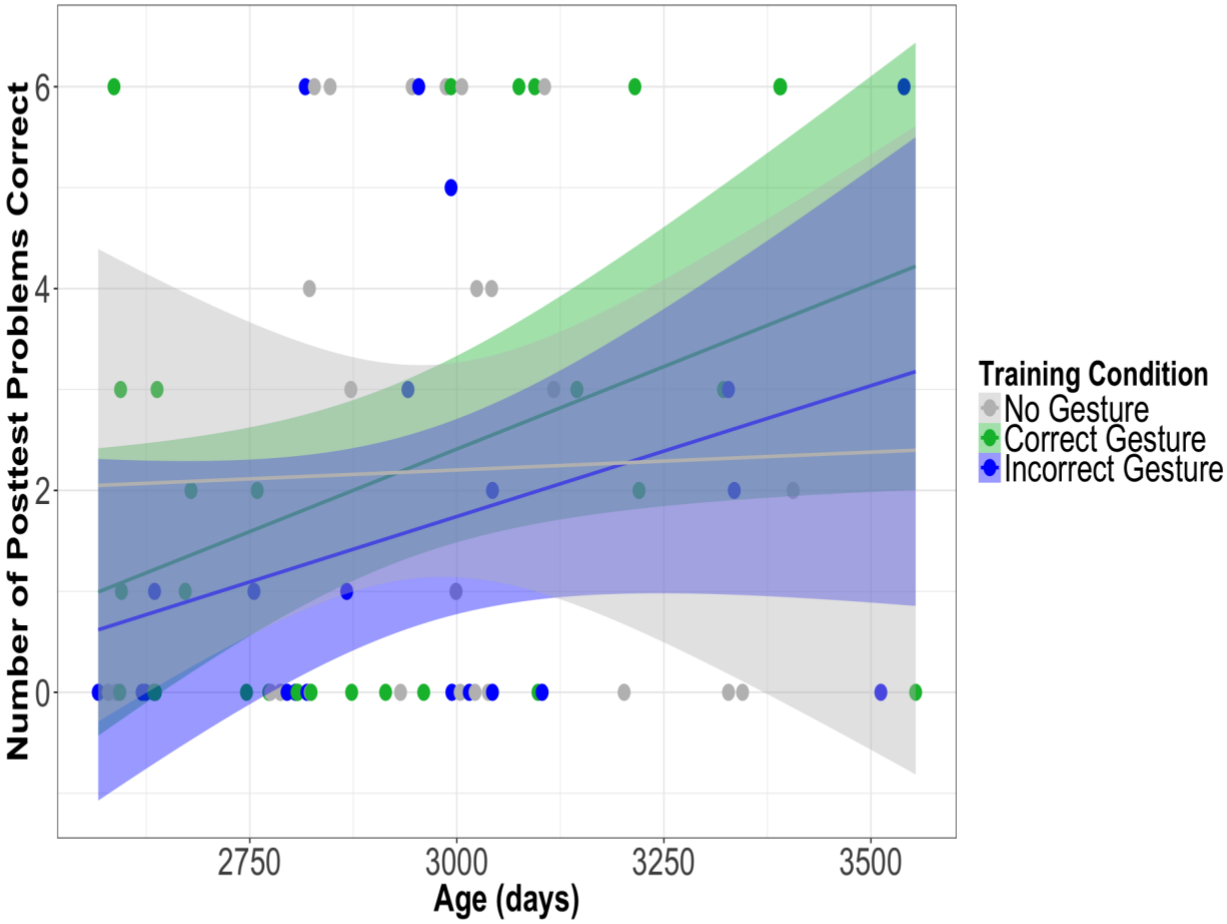


Figure 15: Relationship between age and posttest performance across the three training conditions

I next looked to see if there were any relationships between verbal or spatial working memory and learning across the training conditions. A regression revealed a trending main effect for the no gesture condition ($p = 0.051$, $\beta = 4.901$) and a significant interaction between the no gesture condition and verbal working memory ($p = 0.037$, $\beta = -0.465$), such that greater working memory was associated with less learning in that condition (Figure 15). As you can see in Figure 16, there was a similar relationship between spatial working memory and learning for the incorrect gesture group, but none of the main effects or interactions were significant.

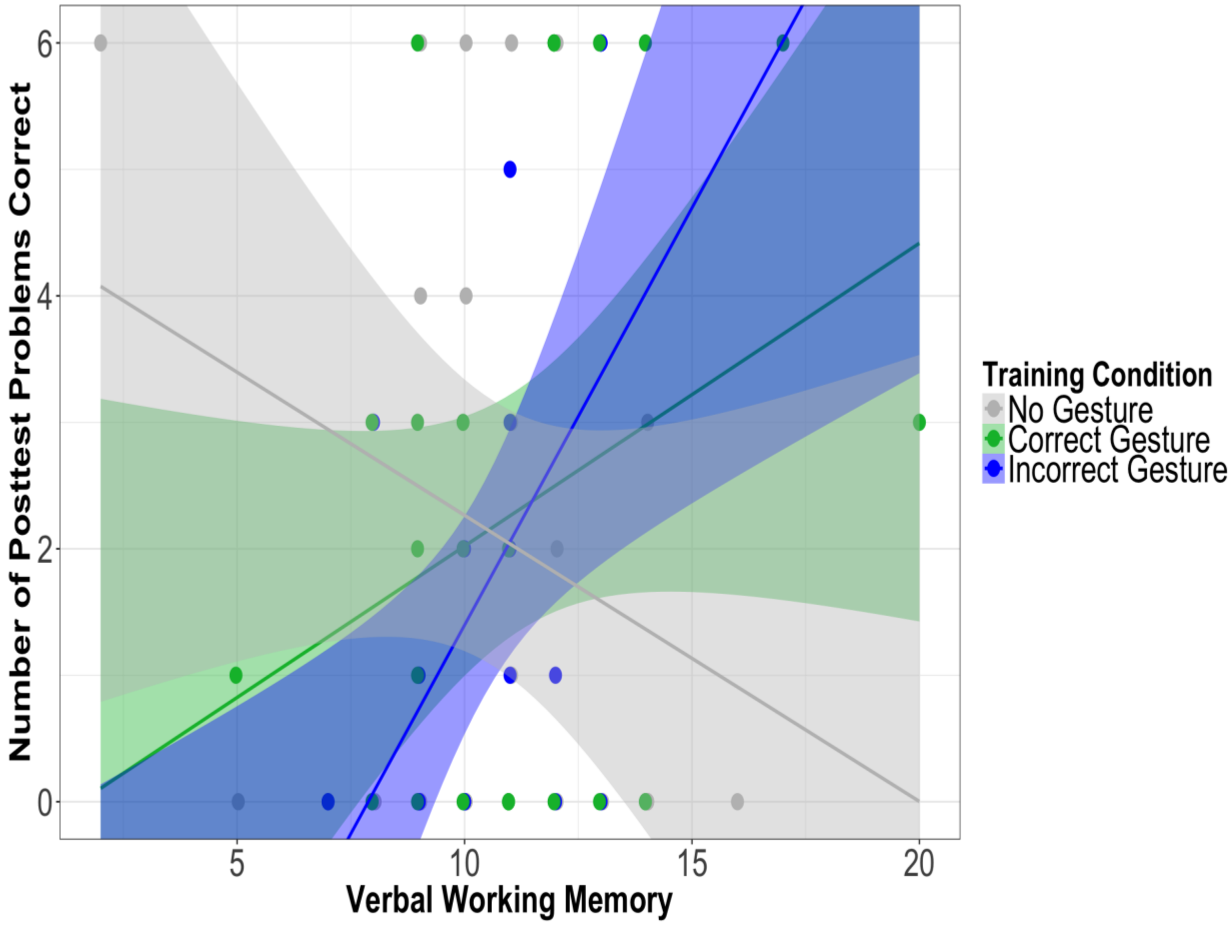


Figure 16: Relationship between verbal working memory (forward+backward digit span score) and posttest performance across training conditions

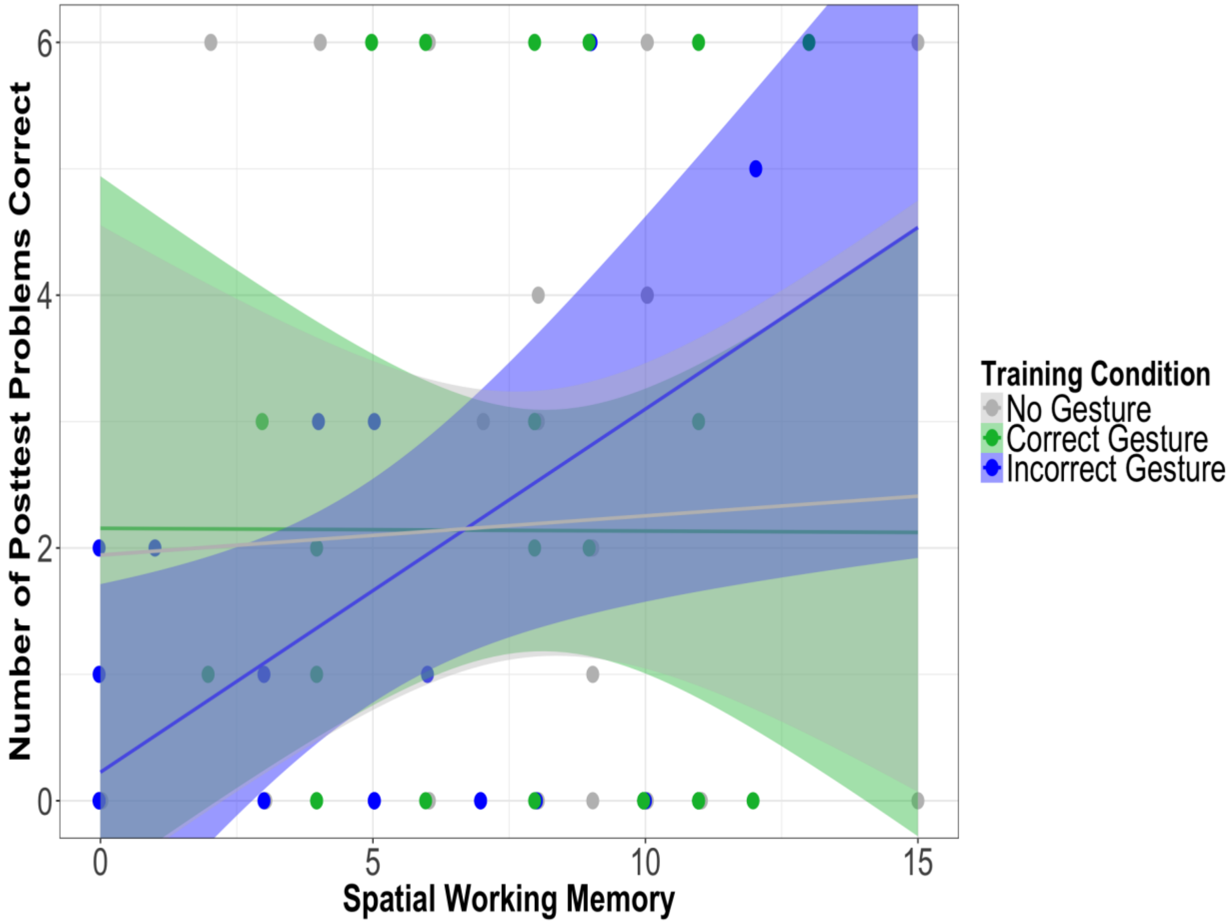


Figure 17: Relationship between spatial working memory (forward+backward corsi block score) and posttest performance across training conditions

In order to investigate the potential moderating role of socio-economic status on learning in my sample, I looked at the relation between household income and posttest performance. On average, parents had 16 years of education (a bachelor's degree) and an average family income level of between $50,000 and $74,999 (ordinal scale ranging from 1=less than $20,000 to 7=greater than $150,000). Income and parental education were positively correlated (r = .55), so I just focused on one variable, though future work could combine these variables to create a composite measure of SES.

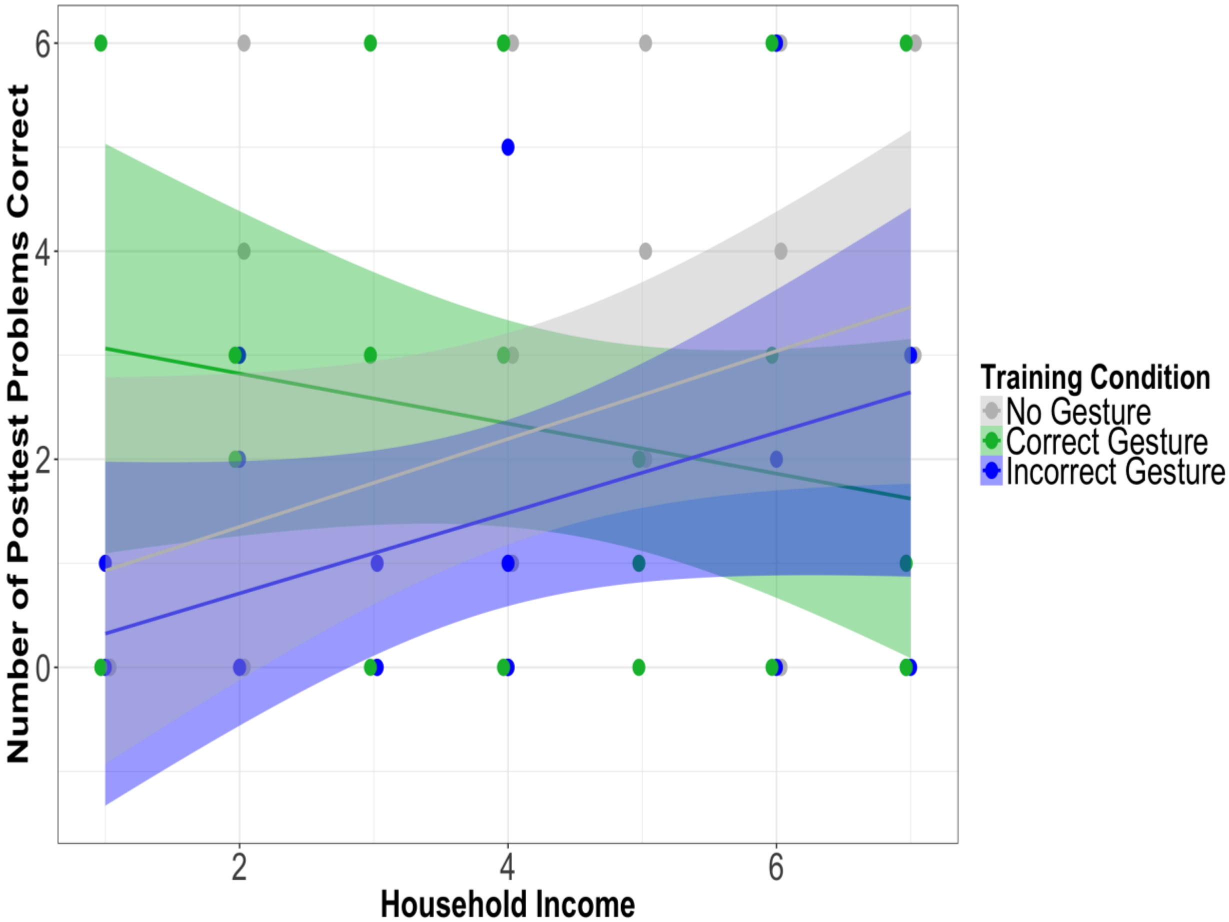


Figure 18: Interaction between income and training condition on posttest performance (for non-knowers)

As you can see in Figure 17, there was an interaction between income and training condition on learning. As my main interest was in comparing the correct and no gesture conditions (and the incorrect gesture graphically resembled the no gesture condition), I put those into a regression and found a trending main effect of training condition ($p = 0.088$), no main effect of income ($p = 0.312$), and trending interaction ($p = 0.053$), with higher income being positively related to learning for children in the speech alone training condition, but higher income negatively related to learning for children in the instructed gesture group. The main effect of training condition and the condition x income interaction become significant when controlling for verbal and spatial working memory (main effect of training condition: $p = 0.034$, main effect of income: $p = 0.110$, interaction: $p = 0.026$). This result suggests that producing (correct) gestures may be particularly beneficial for lower income students, which aligns with past studies that found a benefit of gesture instruction compared to speech alone for samples of children with a lower average income than the present study. A study by Rowe and Goldin-Meadow (2009) found SES differences in the way children use gesture, but future research should further examine the interaction between gesture and SES in learning contexts. Given this finding, I controlled for income and working memory in the analyses for chapter three, which examined individual differences in math anxiety as a potential moderating factor in the effects of learning from gesture instruction.

CHAPTER THREE: MATH ANXIETY AND GESTURE

Mathematics anxiety is an insidious issue in the U.S. that has captured much interest in recent decades (Chiu and Henry, 1990; Hembree, 1990; Wu et al., 2012). Defined by Richardson & Suinn (1972) as "feelings of tension and anxiety that interfere with the manipulation of numbers and the solving of mathematical problems in a wide variety of ordinary life and academic situations," math anxiety has been linked to numerous poor learning and achievement outcomes. Children with math anxiety experience decreased grades, poor standardized test scores, low motivation to take advanced math classes, and avoidance of math-based or STEM careers, which severely limits future employment opportunities (Ashcraft & Krause, 2007; Suinn et al., 1988; Hembree, 1990). Math anxiety has been found to be negatively related to math achievement in part because it can cause negative thoughts and ruminations that co-opt working memory resources needed to solve difficult math problems in the moment (Ashcraft, 2002; Ashcraft & Kirk, 2001; Hembree, 1990; Lyons & Beilock, 2012; Park, Ramirez, & Beilock, 2014). Evidence consistent with this hypothesis comes from behavioral (Ashcraft & Kirk, 2001; Park et al., 2014) and brain imaging studies (Young, Wu, & Menon, 2012; Lyons & Beilock, 2012). Previous work suggests that children as young as first grade can experience anxiety about math, so it is important to develop ways to help mitigate the negative effects of math anxiety on math performance (Ramirez et al., 2013).

Research on mechanisms of math anxiety suggests that the decreased performance of highly math-anxious individuals is not reflective of their actual math capability. Lowering math anxiety has been found to result in a reciprocal increase in math performance, even in children with learning disabilities specific to math (Hembree, 1990; Kamann & Wong, 1993). Meanwhile, special training to improve math competence does *not* result in a reciprocal decrease in feelings of anxiety regarding math (Hembree, 1990). The literature instead posits that the loss of performance from math anxiety is actually due to a shortfall of cognitive resources. Studies have shown that worry about math and performance in a math task take up working memory resources needed to adequately engage with a problem and solve it, which leads to increased reaction time and error rate, especially with larger operands (Ashcraft & Krause, 2007; Ashcraft & Kirk, 2001; Beilock, 2010; Young, Wu, & Menon, 2012).

This is the first study to look at gesture as a potential intervention for the negative effects of math anxiety. Since math anxiety has been shown to take up mental resources while solving math problems, gesturing could help reduce this cognitive load. Gesture instruction could be a cheap and effective intervention for improving learning and achievement outcomes for children with high anxiety about mathematics, thereby mitigating some of the cascading deleterious effects of math anxiety.

Results and Discussion

Individual differences in math anxiety

Figure 18 shows the overall distribution of non-knowers' scores on the Scale for Early Math Anxiety (SEMA). In this questionnaire, higher scores represent higher levels of math anxiety, whereas lower scores represent lower levels of math anxiety. There were few children in our sample with extremely high levels of math anxiety. Scores on the scale can range from 20-100, and our sample ranged from 20-77. This could be due to self-selection bias, since parents of children with extreme math anxiety might be less likely to bring their child into a lab to participate in a study on how children learn math. Also, we had one child with such high math anxiety that he chose to terminate the study after the pretest, so could not be included in this sample. Overall mean math anxiety on the SEMA for non-knowers (n = 55) across conditions was 35.52 (SD = 12.53). Among non-knowers in the correct gesture condition (n = 29), the mean SEMA score was 35.84 (SD = 12.25), and in the no gesture condition (n = 26) the mean was 35.15 (SD = 13.07). Our mean scores are similar to those reported by Wu and colleagues (M = 34.35, SD = 11.60), who created the scale and found significant relations between SEMA scores and math achievement in their sample.

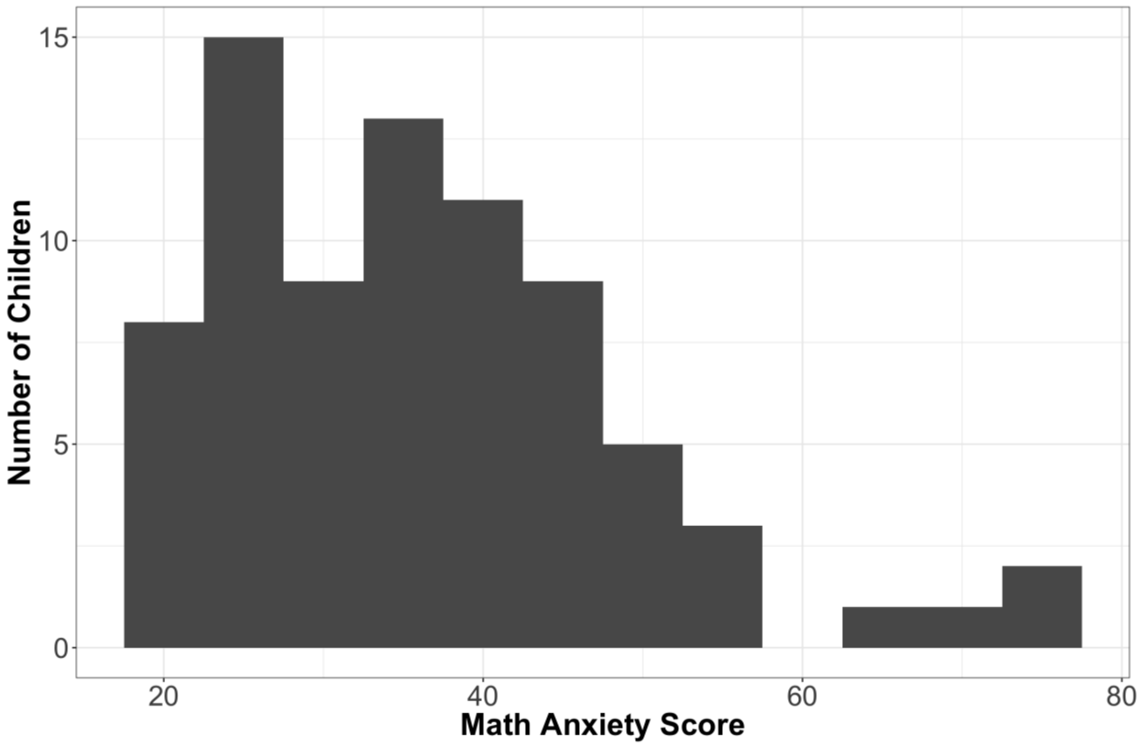


Figure 19: Distribution of non-knowers' scores on the Scale for Early Math Anxiety

In my sample, math anxiety and income were negatively related ($p = 0.004$, $\beta = -2.126$). Math anxiety was also negatively related to both verbal working memory ($p = 0.006$, $\beta = -1.504$) and spatial working memory ($p = 0.011$, $\beta = -1.009$). There was also a significant interaction (Figure 19) between income and verbal working memory in predicting math anxiety scores (main effect of income: $p < 0.001$, main effect of verbal working memory: $p < 0.001$, interaction: $p = 0.004$). There were no gender differences in math anxiety (female M = 37.672, male M = 32.522, $t(52.990) = 1.602$, $p = 0.115$).

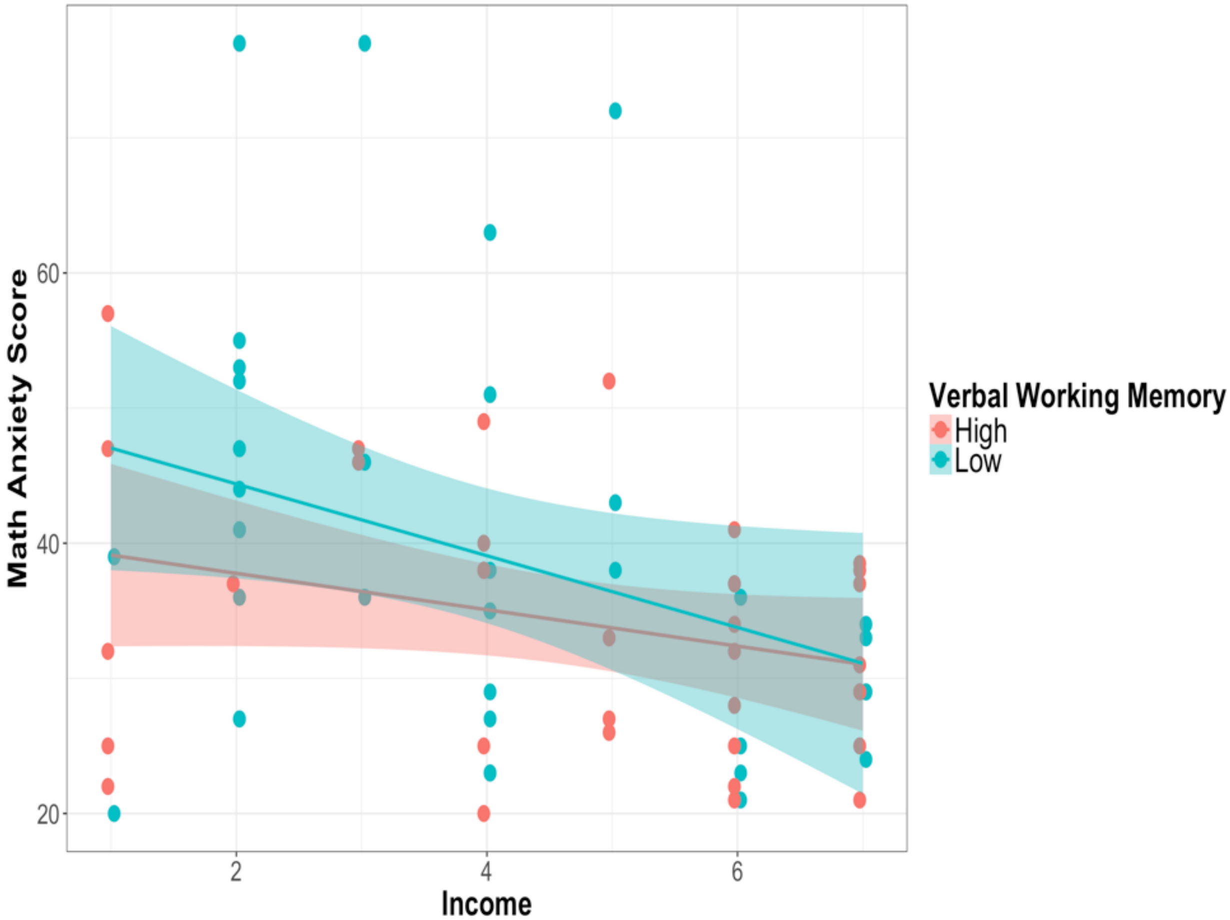


Figure 20: Relationship between yearly household income (1: < $20,000, 7: >$150,000) and math anxiety binned by a median split on digit span scores

Children's self-reported competence in math was negatively associated with math anxiety ($p = 0.001$, Figure 20), as lower scores reflect greater competence.

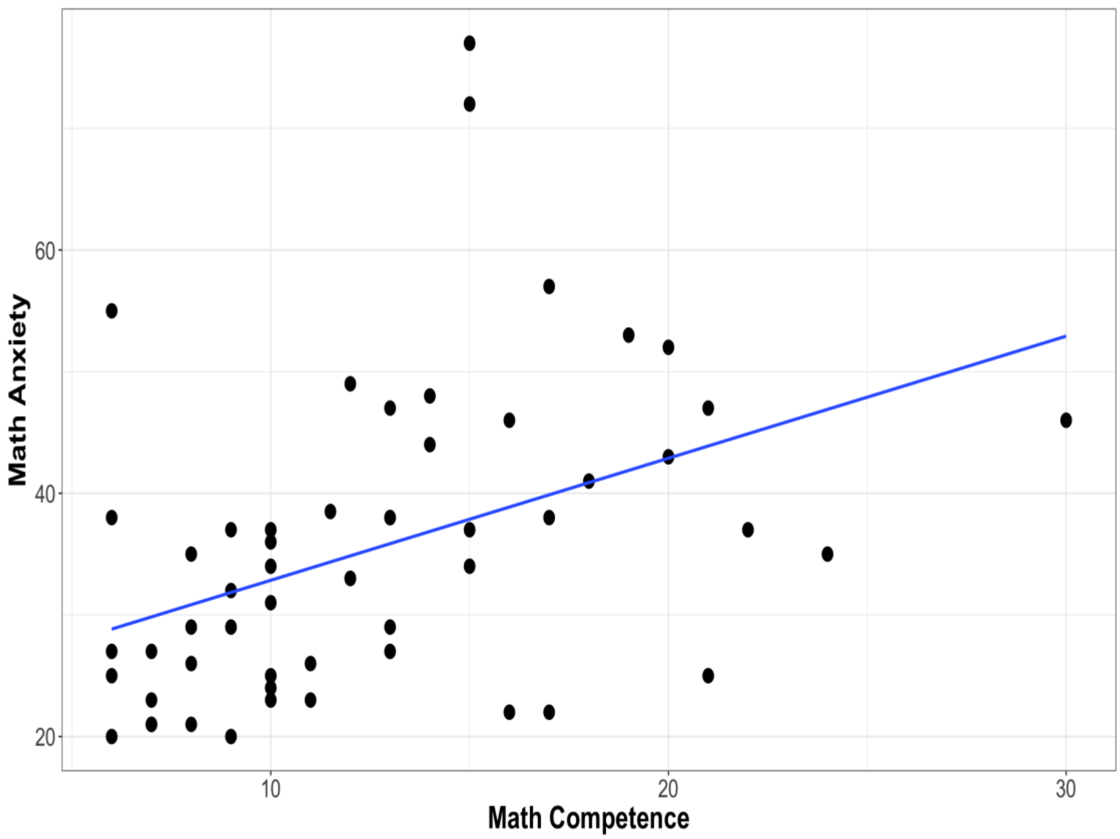


Figure 21: Relationship between math competence scores and math anxiety

Math competence was also related to posttest performance (see Figure 18). Controlling for income and math anxiety, there was a significant main effect of math competence on learning ($p = 0.016$), a main effect for the no gesture condition ($p = 0.012$), and a significant interaction between math confidence and condition on learning ($p = 0.009$). In the no gesture condition, greater competence is linked to better performance, but the opposite pattern emerged in the two gesture conditions. Thus, gesture may be a particularly beneficial learning tool for children with lower perceived competence in math.

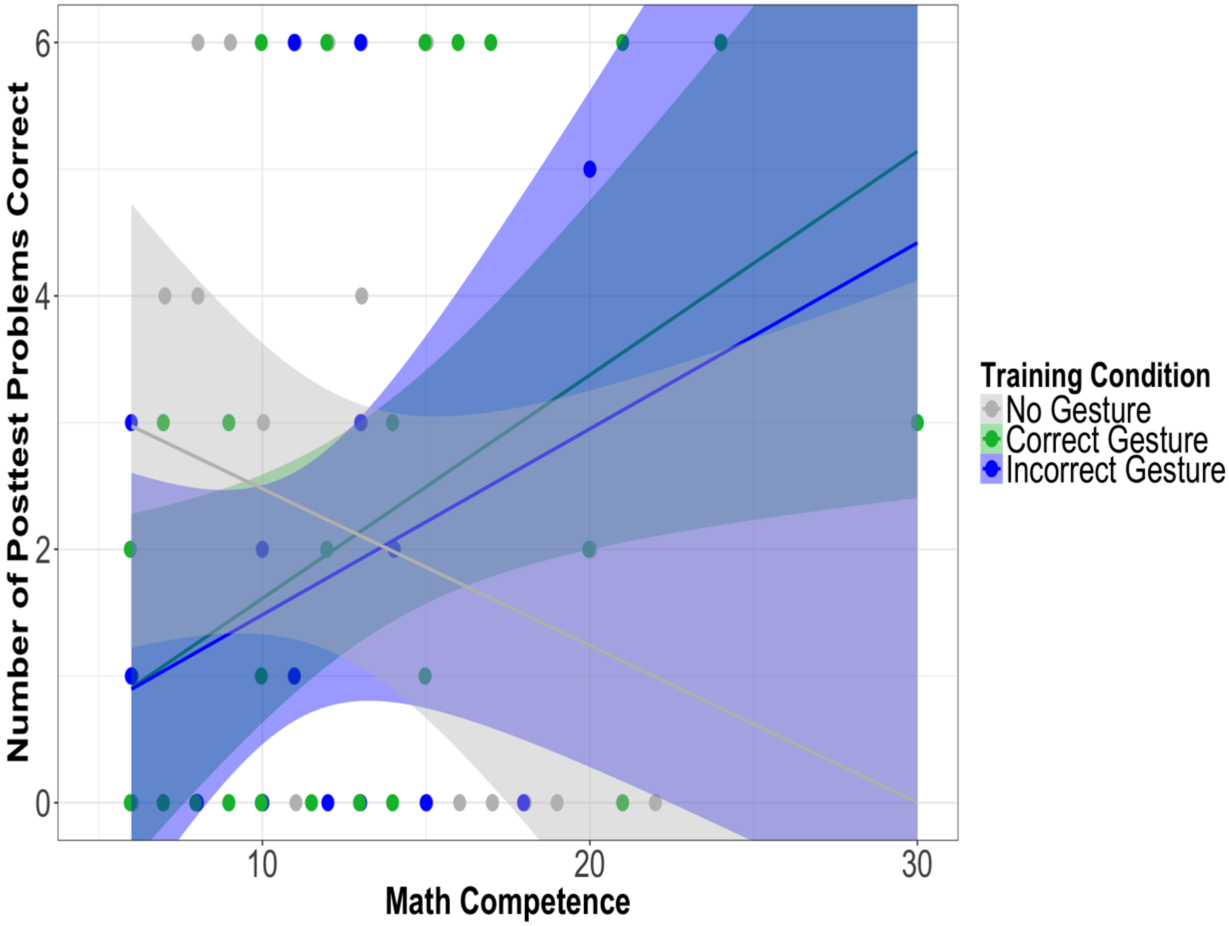


Figure 22: Relationship between math competence and posttest performance across the training conditions

Math anxiety and rates of spontaneous gesturing

If children with higher math anxiety are experiencing greater cognitive load while explaining how they got their answers on the pretest, we would predict that they might gesture to lighten some of that load. To address this possibility, I first compared the mean math anxiety score for spontaneous gesturers (M = 35.246) and non-gesturers (39.607). While spontaneous gesturers had slightly lower math anxiety, the difference was not statistically significant ($t(21.086) = -1.205$, $p = 0.242$).

I next looked at the number of pretest problems (ranging from 0 to 6) on which children produced at least one gesture. As you can see in Figure 22, this was not normally distributed, so I used Poisson regression to analyze the relationship between spontaneous gesturing and math anxiety for knowers and non-knowers.

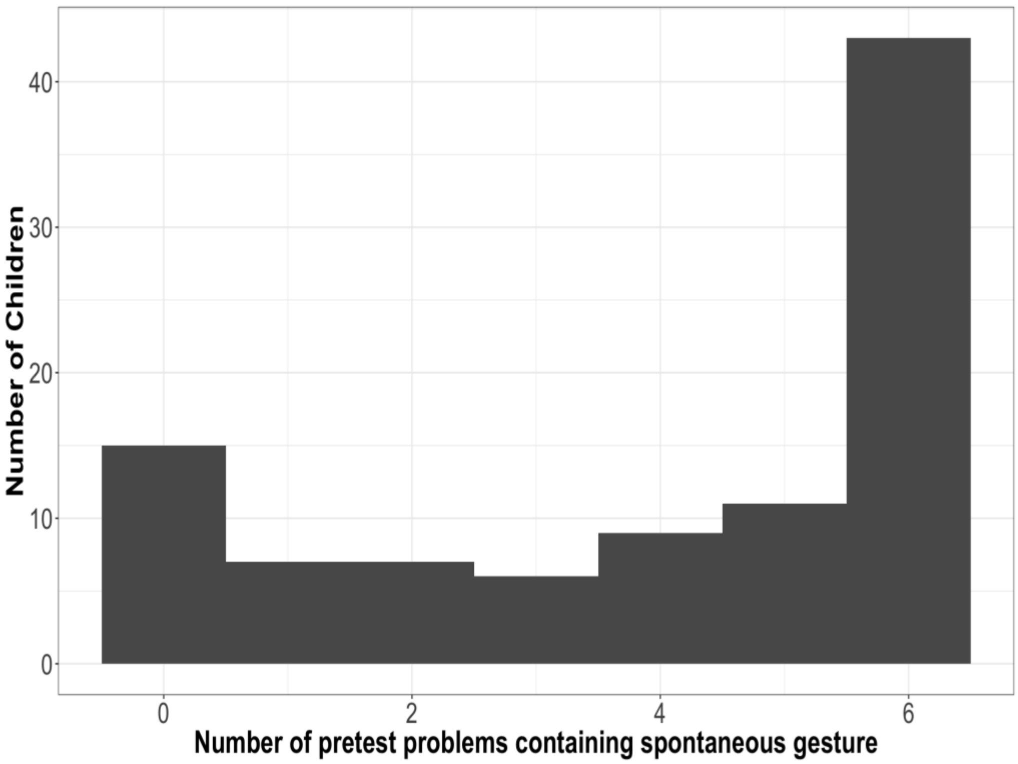


Figure 23: Distribution of pretest explanations on which children spontaneously gestured

Controlling for income, age, and verbal/spatial working memory, there was a significant relationship between number of spontaneous gestures and math anxiety for knowers, but not non-knowers (main effect of number of gestures: $p < 0.001$, main effect of knowledge group: $p < 0.001$, interaction: $p < 0.001$). As you can see in Figure 23, knowers with higher levels of math anxiety spontaneously gestured during pretest explanations significantly more than knowers with lower levels of math anxiety.

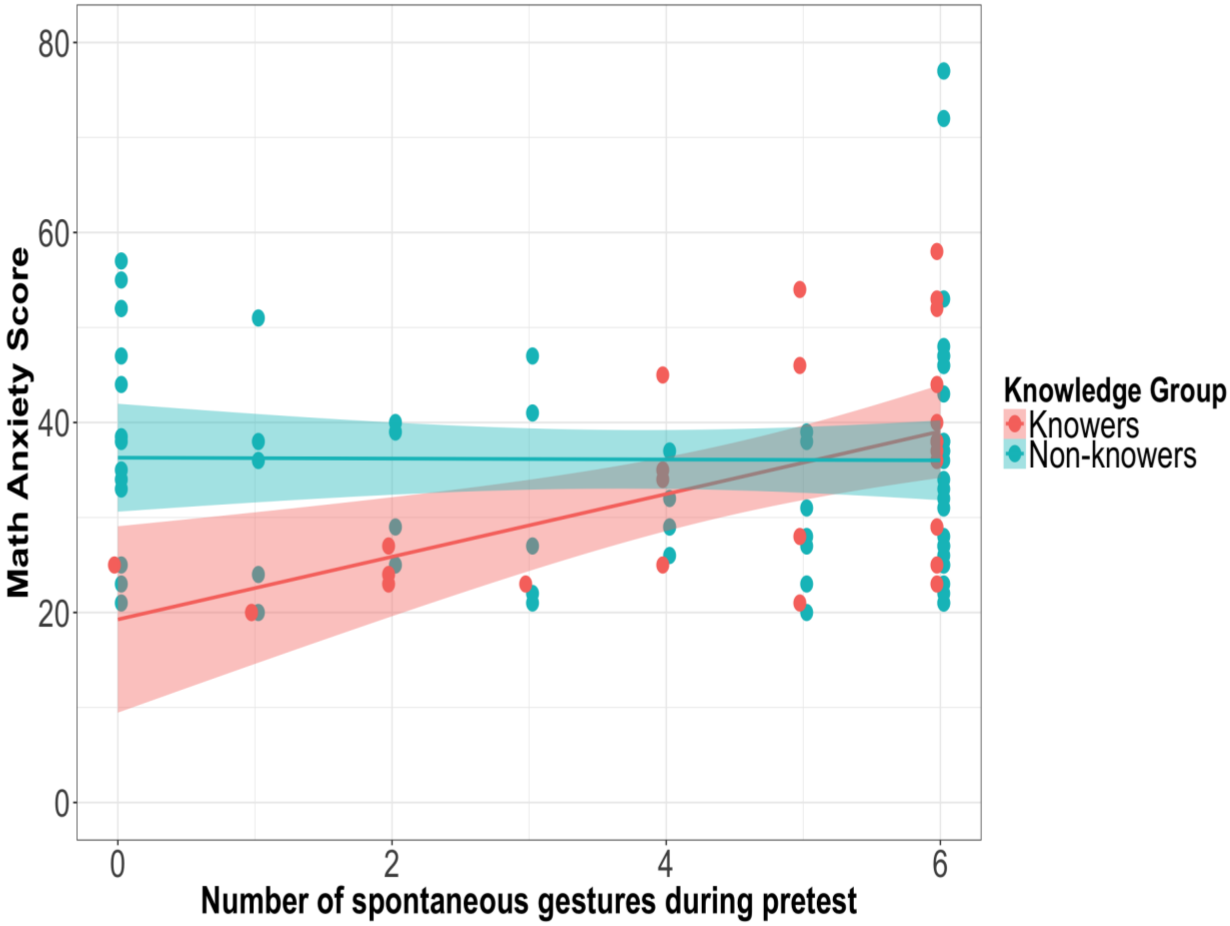


Figure 24: Relationship between math anxiety score and spontaneous gesture production during pretest explanations

Effects of instructed gesture and math anxiety on learning

Figure 24 shows the distribution of posttest performance (including trained and near transfer problems) for all of the children who got none of the pretest problems correct. Since there was a meaningful number of children who scored between none and all correct, I analyzed posttest performance as a continuous variable, rather than classifying children into learners and non-learners.

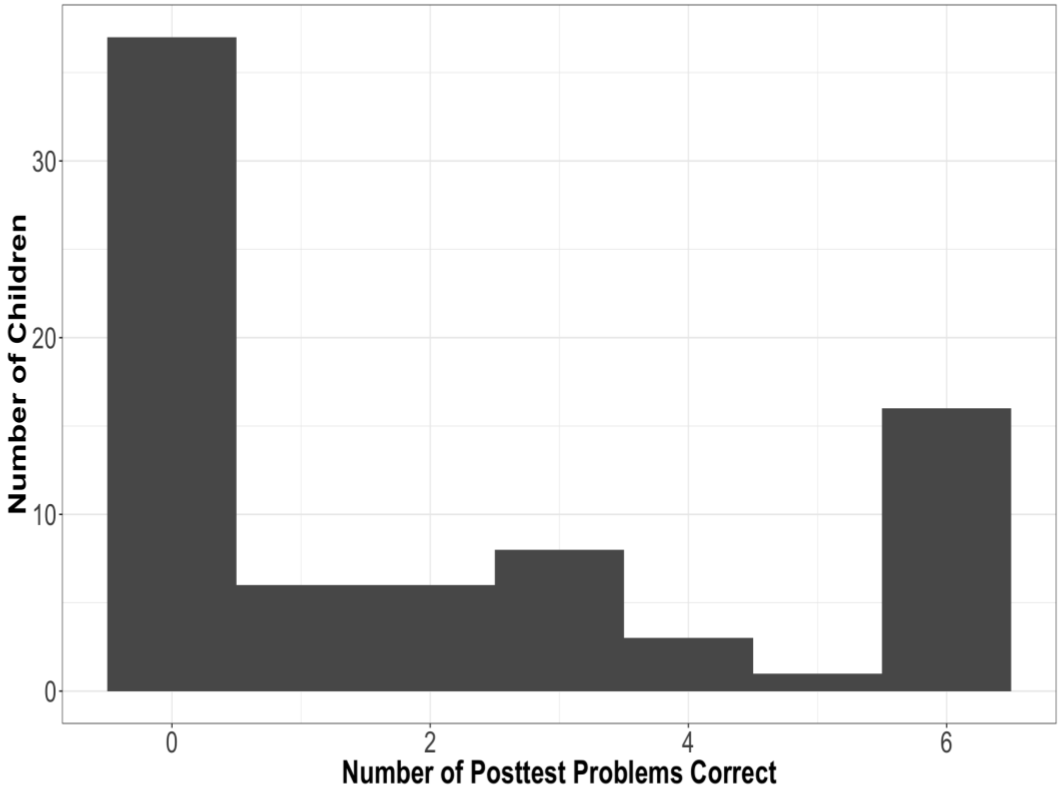


Figure 25: Distribution of posttest scores for non-knowers

Given the relation between income and learning reported in chapter 2, I controlled for income when examining the relation between learning and math anxiety. As predicted, children with higher levels of math anxiety performed worse than children with lower levels of math anxiety in the no gesture condition, but the opposite occurred in the correct gesture condition (main effect of condition: $p = 0.062$, main effect of math anxiety: $p = 0.086$, interaction: $p = 0.052$). Controlling for income, age, and working memory the interaction between training condition (correct gesture vs. no gesture) and posttest performance was statistically significant (main effect of condition: $p = 0.034$, main effect of math anxiety: $p = 0.041$, interaction: $p=0.020$, see Figure 25).

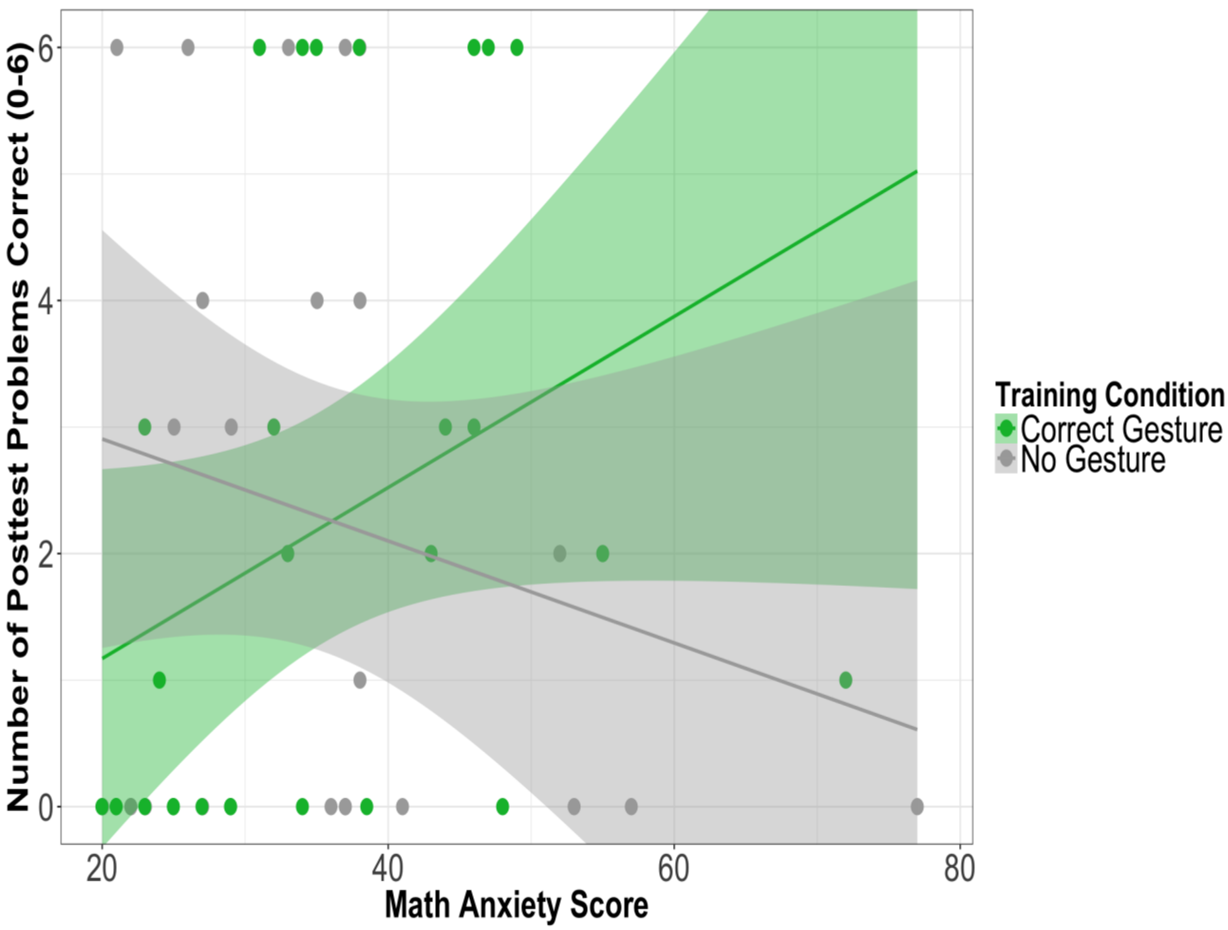


Figure 26: Relationship between math anxiety and training condition

Since past research suggests that gesture may be a particularly powerful tool for generalization (Novack et al., 2014), I looked at performance for trained vs. transfer problems (near and far transfer combined) at posttest (controlling for income, age, and working memory). Similar patterns emerged, but the findings were stronger for transfer problems (main effect of condition: $p = 0.013$, main effect of math anxiety: $p = 0.036$, interaction: $p = 0.016$) compared to trained problems (main effect of condition: $p = 0.036$, main effect of math anxiety: $p = 0.072$, interaction: $p = 0.027$).

I propose that gesturing was able to buffer the deleterious effects of math anxiety on learning by lightening the cognitive load of children experiencing high cognitive load due to a greater number of anxious thoughts during the math lesson. There are a few mechanisms that might explain the effect of gesturing for children with higher levels of math anxiety. First, gesturing might free up working memory resources for problem solving, compensating for those taken up by anxiety. Second, though not mutually exclusive, gesturing may allow individuals to not only engage with the problem explicitly, but also to access the implicit information about the problem "stored" within gesture that would likely be unaffected by conscious worry about performance involved in math anxiety.

Do differences in self-reported math anxiety manifest on a physiological level? There was no relationship between math anxiety and parasympathetic activity during the baseline video ($p = 0.584$), while solving the written pretest ($p = 0.361$) or during the windows around solving each of the training problems ($p = 0.842$). Although termed math *anxiety*, the phenomenon may be different from traditional forms of physiological anxiety such as when under threat or exhibiting a stress response. Our finding conceptually replicates those of Chang and colleagues (2014), who found no differences in a number of measures of autonomic nervous system activity between children with high vs. low levels of math anxiety. It is interesting that the behavioral differences we see in learning across levels of math anxiety are not reflected in our measure of parasympathetic activity. It is possible that the relationship between math anxiety and impaired math performance may not just be explained by differences in cognitive load. Cognitive load could still differ between children with higher vs. lower math anxiety, but simply not be reflected in our particular proxy measure of cognitive load (RMSSD).

CHAPTER FOUR: PARASYMPATHETIC CORRELATES OF CHANGES IN KNOWLEDGE

In this final chapter, I asked whether there are parasympathetic differences while solving problems during training between children who do and don't learn. I had four differentiable groups in my study that varied in terms of their stability and accuracy of their understanding of math equivalence. Knowers, who get all six pretest problems, also get all six problems correct during training, and thus do not undergo a change in knowledge. Similarly, non-knowers who never solve a problem correct during pretest, training, or posttest, are stable in their incorrect understanding overtime. In contrast, there are two groups of non-knowers who experience a change during training by solving at least one problem correctly. Children who get their first correct answer during training and then maintain that knowledge on the posttest can be said to be undergoing a fundamental change in knowledge. However, children who get at least one problem correct during training but then get all of the posttest problems wrong appear to be changing, but that change is transitory.

Results and Discussion

To investigate the moment of learning (across training conditions), I first looked at non-knowers who solved at least one problem correct during training and had clean enough physiological data during training to analyze (38 out of 79 total non-knowers). Figure 26 shows the distribution of trials on which these participants got their first correct answer.

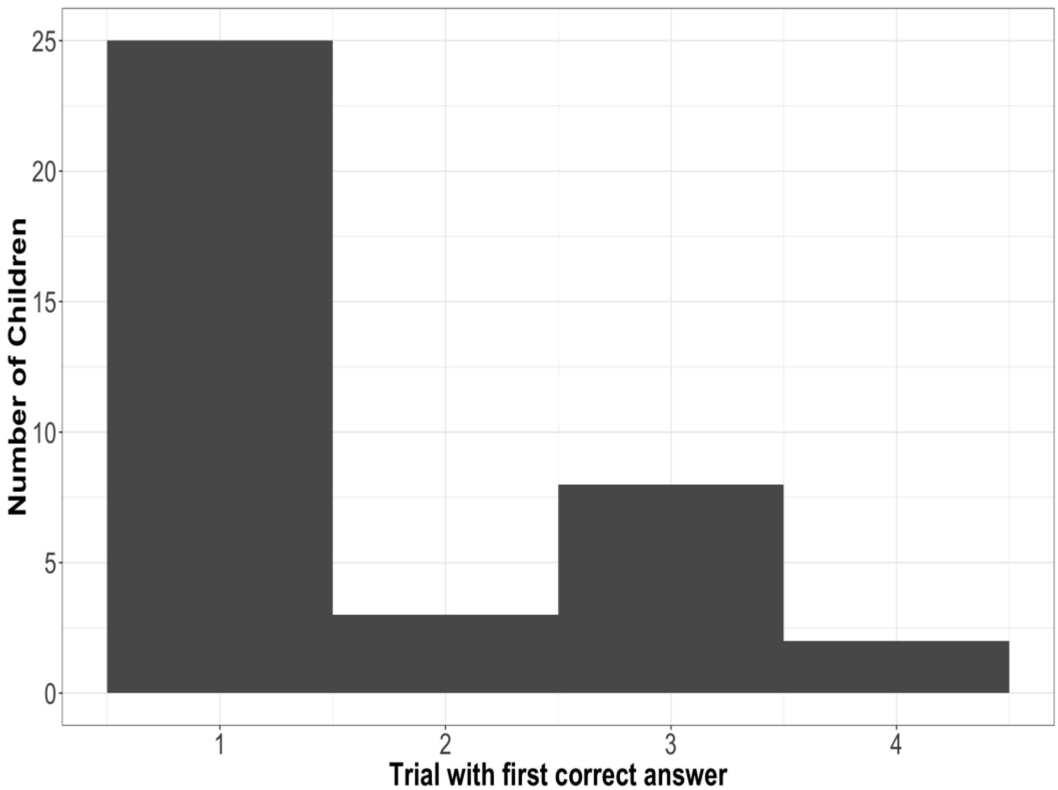


Figure 27: Distribution of training problems on which non-knowers got their first correct answer

Not all children who get at least one training problem correct during training actually learn the concept of math equivalence. For some children, they may try out a correct strategy on a given problem (or get the correct answer by accident using an incorrect strategy), but then do not continue to consistently use that correct strategy. I categorized non-knowers (0 correct at pretest) into those who got at least one correct answer during training and then solved at least two problems correct on the posttest (the "correct and keep" group, n = 23), compared to non-knowers who got at least one correct answer during training but solved none of the posttest problems correctly ("correct and lose," n=13). There were no physiological differences between these classifications of children at baseline ($F(4,75) = 0.356$, $p = 0.839$), so I used raw RMSSD values rather than change from baseline scores for the analyses.

To investigate changes around the moment of learning, I looked at parasympathetic activity during the 10 second time window surrounding each child's start of writing their answer (the last possible moment insight could occur), as well as the 10 seconds before that window, during which children produced the instructed gesture and/or speech strategy. There was a significant difference in parasympathetic activity between the "correct and keep" and "correct and lose" groups when looking at the change in RMSSD from the window right before to during writing their first correct answer ($p = 0.037$). Interestingly, there was no difference in children's confidence in their training answers (reported after the posttests) for these two groups ($t(21.432) = 1.163$, $p = 0.258$).

To compare these groups to knowers (who got all training problems correct) and non-knowers that never got a problem correct during training or posttest, I randomly assigned a "first correct" training trial for each of these children, since they didn't have an actual first correct answer during the training phase. To assign these children a fake "first correct" training problem for comparisons to the children who really did get their first correct answer during training, I ran 10,000 simulations using R statistical software, with each simulation outputting one of the first four training problems as each participant's "first correct" trial, according to the same distribution of actual first correct trials shown in Figure 26. I then calculated the average parasympathetic activity associated with each of the 10,000 "first correct" trails for each of these children in the "always correct" and "never correct" groups.

I then calculated the difference in these children's RMSSD values from the 10 second window before children started writing their first correct answer to the 10 second window around the moment their marker starts writing their solution. Figure 27 shows the average difference (RMSSD around writing – RMSSD before writing) for all four groups of children: those who got their first correct answer during training and kept that knowledge ("correct and keep"), those who got their first correct answer during training but lost that knowledge ("correct and lose"), those who got all of the pretest and training problems correct ("always correct"), and those who never solved a problem correct during the experiment ("never correct"). As you can see, children who got all of the problems correct and children who got none correct have similar patterns of parasympathetic activity, which we would expect since they are not experiencing any change in knowledge (they either have stable correct knowledge or stable incorrect knowledge).

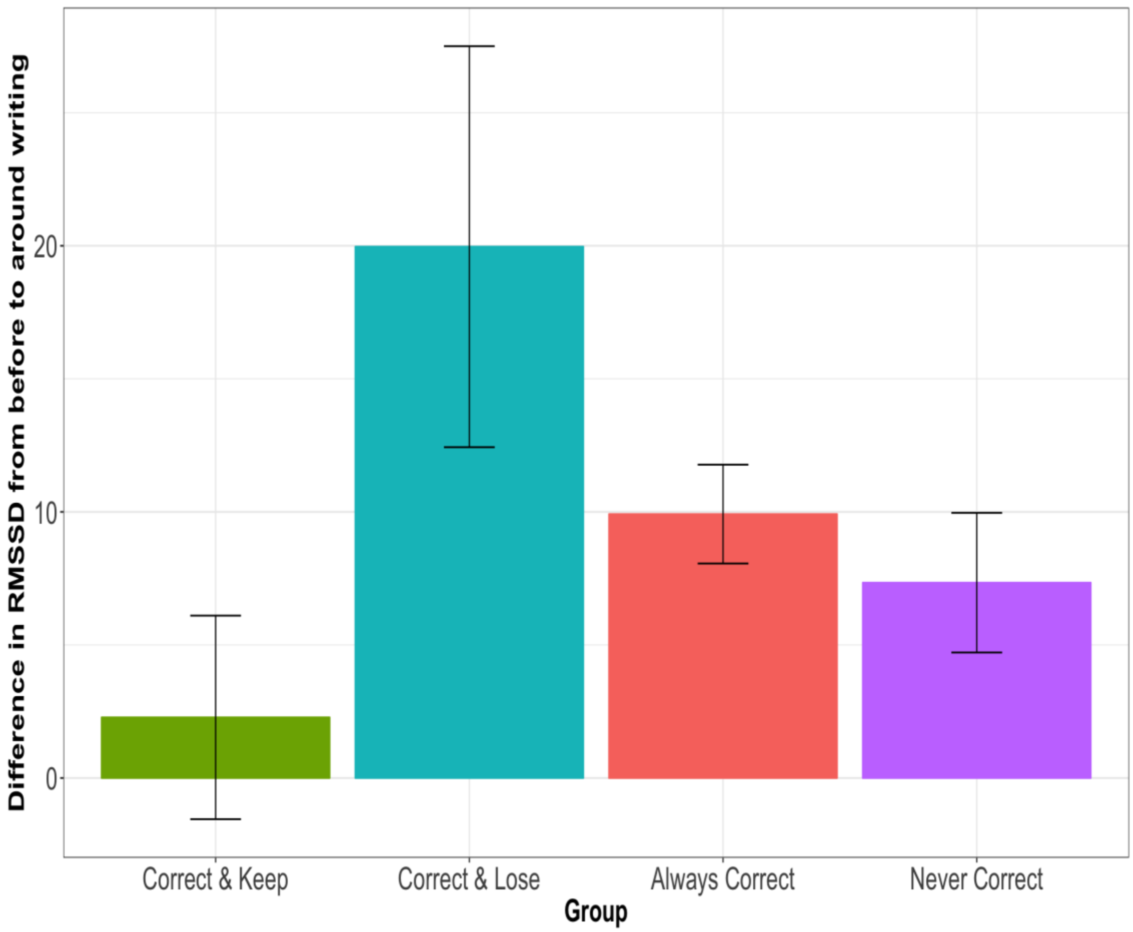


Figure 28: Changes in parasympathetic activity from the 10 second window before writing the "first correct" answer to the 10 second window around the start of writing the answer for children whose knowledge changes vs. stays the same

While there was no significant difference in parasympathetic activity between the time windows before and while writing the solution for children in the "correct and keep" group (t(41.3) = 0.37, p = 0.716), there were significant or trending differences for the other three groups (“correct and lose”: t(17.2) = 1.75, p = 0.098; “always correct”: t(47.3) = 2.17, p = 0.035; “never correct”: t(31.6) = 1.52, p = 0.138). Unlike these three groups who have an increase in parasympathetic activity as they write their answer (reflecting a decrease in cognitive load), children who are fundamentally changing during this period (“correct and keep”) maintain a similar level of parasympathetic activity (and presumably cognitive processing) from when they perform the instructed strategy through the period of solving the problem.

To track changes in this patterning over time, I compared parasympathetic activity during the first correct problem to the following two training trials (Figure 28). While the “always correct” and “never correct” children (the stable knowledge groups) show a consistent pattern across these three training problems, the unstable knowledge groups have different patterns of parasympathetic activity. After the trial containing their “insight” moment, the “correct and keep” group starts to resemble the other groups who have a larger change in parasympathetic activity from pre-solving to writing their answer. In contrast, children in the “correct and lose” group show the opposite pattern with a significant decrease in degree of parasympathetic change around their solutions on the two problems following their fleeting insight moment. Although these children do not solve any additional problems correctly (and do not consciously report a lack of confidence in their answers), it is possible that the act of producing one correct answer creates a shift in these children at a physiological, perhaps implicit, level that persists after this transient insight moment.

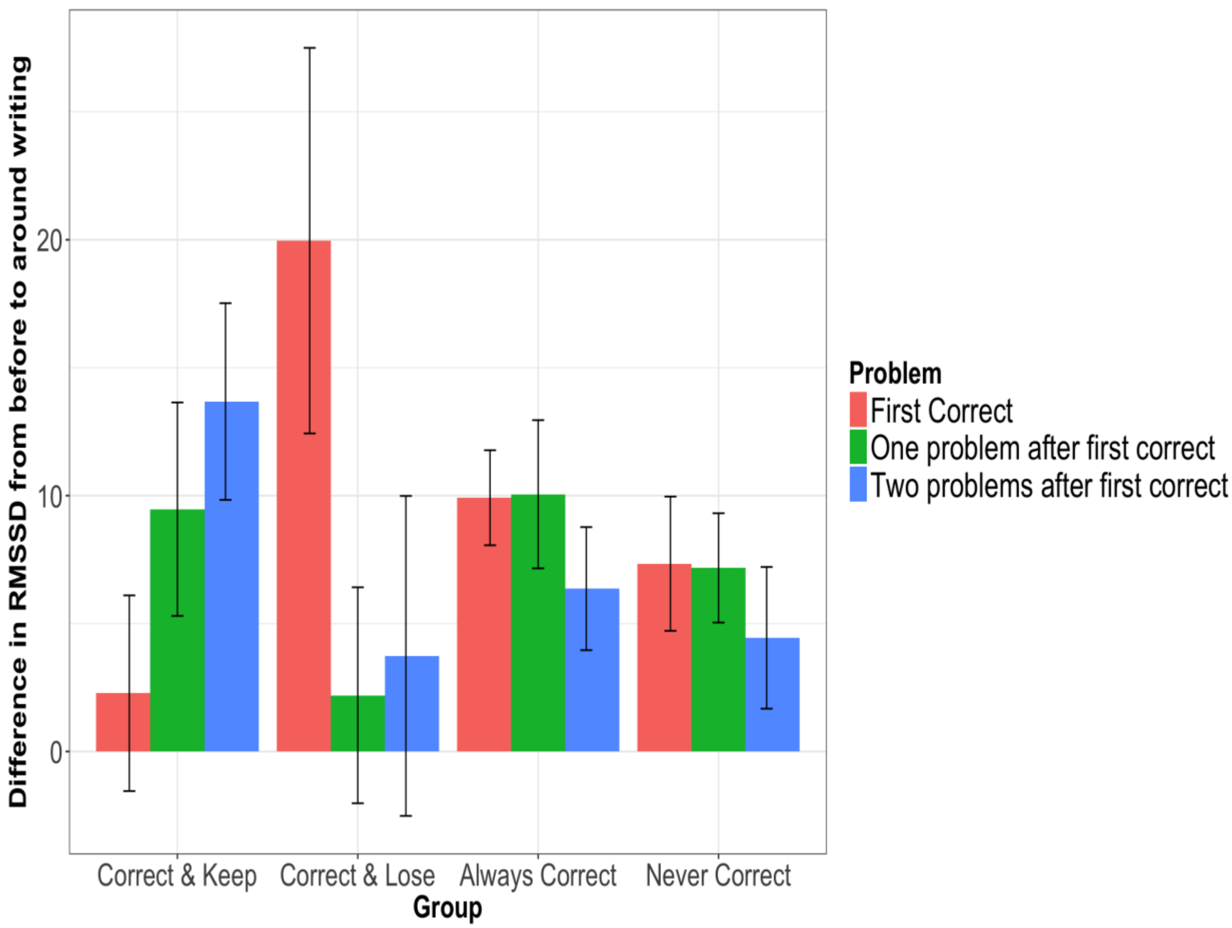


Figure 29: Change in parasympathetic activity for each group from the window before solving to the window around writing solutions for the first correct problem during training and the following two problems

GENERAL DISCUSSION

The current work is the first of its kind to use a psychophysiological measure to investigate the role of gesture in expressing knowledge and affecting learning. The results reported in this dissertation, both significant and trending, suggest the promising potential of adding physiological measures to the field of gesture studies, as they can provide unobtrusive, continuous, and temporally fine-grained tracking of cognitive states throughout the learning process beyond what behavior alone can reveal.

In my first chapter, I showed a significant relationship between parasympathetic activity and the number of gesture-speech mismatches children produced while explaining their pretest solutions (regardless of solution accuracy). The negative relationship between number of mismatches and RMSSD provides additional evidence for the hypothesis proposed by Wagner and colleagues (2004) that mismatching gestures are associated with higher cognitive load than non-mismatching gestures. Entertaining two strategies at once seems to tax more cognitive resources than only having one strategy in mind.

This finding contradicts evidence presented by Ping and colleagues (2010) that mismatches lightened cognitive load for children explaining Piagetian conservation. Their argument was that mismatching differentially affects cognitive load depending on the gesturer's understanding of the task. Whereas the study by Wagner and colleagues examined adults who were experts with regard to the math problems they were solving, Ping and colleagues observed children who were novices in conservation. In my study, the more mismatches children produced, the greater their cognitive load (as inferred from RSA) for both knowers (experts) and non-knowers (novices). While the participants in my study were children like in the study by Ping and colleagues, they were older and explaining a different concept in a different domain. In the Ping paper, mismatches were associated with lighter cognitive load than non-mismatches only when the objects in the conservation task were present, not when they were absent. While children in my study were pointing to “present” numbers, rather than empty space, mathematical symbols are more abstract than physical objects. Future work should attempt to isolate the variables that may determine whether producing gesture-speech mismatches compared to matches increases, decreases, or does not affect cognitive load. These variables include the age of participants, their knowledge of the task at hand, and the task domain, including the abstractness of the gestures’ referents.

While RSA appears to track variations in people’s implicit knowledge from problem to problem, it did not reveal differences in my sample within individuals on problems on which they mismatched verses did not mismatch. These findings suggest that children who produce mismatches are in a different cognitive state than children who do not mismatch, and the more often a child mismatches, the more he or she is in a state of transition. However, I cannot directly link our observed variations in parasympathetic activity to learning outcomes, since children who produced mismatches in my sample were not significantly more likely to learn than non-mismatchers, unlike in previous studies. This may be due to demographic differences across studies. The fact that I also did not replicate previous findings regarding the effects of instructed gesture on learning could have limited my ability to observe relationships between spontaneous gesturing and learning outcomes. Future work should investigate the specific relation between parasympathetic activity, mismatch, and learning in larger, more representative samples.

In chapter two, I investigated whether spontaneous and instructed gesturing affects cognitive load (as measured by RMSSD) compared to not gesturing. For spontaneous gesture, I found a trending negative relationship between number of pretest solutions containing gesture and parasympathetic activity, which is consistent with prior work suggesting that producing gestures lightens cognitive load (Goldin-Meadow et al., 2001; Wagner et al., 2004). I did not find significant differences in parasympathetic activity within spontaneous gesturers on problems on which they gestured vs. did not gesture. Future work examining spontaneous gesturing and cognitive load needs to account for the possibility that children who do not need to lighten their cognitive load do not gesture. For example, one could examine each child's physiological data in relation to that child's general working memory capacity and self-reported confidence for each problem during the pretest explanation phase.

In terms of instructed gesture, my data suggests a trend that movement, including gestures that provide an incorrect strategy, may be associated with lighter cognitive load compared to not gesturing. However, these trending differences in parasympathetic activity do not relate to behavioral learning outcomes, so future studies that do find significant differences in posttest performance across training conditions should examine corresponding physiological differences. Future work should also look within individuals at the moment before their first gesture to see if gesturing lightens cognitive load within the person, and whether this is particularly evident for children who have greater levels of cognitive load to begin with.

In chapter three, I provide the first evidence for the hypothesis that gesture instruction is particularly beneficial for children with higher levels of math anxiety. Since math anxiety and income were negatively correlated in my sample, it is important to note that differences in socio-economic status cannot account for the interaction of gesturing and training condition, as the effect was still significant when controlling for household income. Based on previous research, I propose that this effect is due to gesture's ability to lighten the cognitive load of people whose anxious thoughts about math are taking cognitive resources away from being able to focus on the task at hand (Ashcraft & Faust, 1994; Ashcraft & Kirk, 2001; Faust, Ashcraft, & Fleck, 1996).

Interestingly, parasympathetic activity did not track differences in math anxiety scores in my sample. It is not clear why I did not see a significant relationship, given the previously established relationships between RMSSD and cognitive load and between math anxiety and cognitive load. Although not significant, the correlation between RMSSD while explaining pretest solutions and scores on the Scale for Early Math Anxiety was in the expected negative direction for knowers ($r = -0.180$), with higher math anxiety scores associated with slightly lower RMSSD (there was no relationship for non-knowers, $r = 0.063$). There may be differences in the degree to which children experience math anxiety on a physiological level depending on their knowledge level or confidence on a given problem. It is also possible that the Scale for Early Math Anxiety did not pick up on individual differences in anxiety about math equivalence in particular. Indeed, math anxiety scores were only moderately correlated with children's self-reported nervousness during the written pretest ($r = 0.310$) and while explaining their pretest solutions ($r = 0.291$). These post-hoc ratings of nervousness, which also did not relate to parasympathetic differences during pretest or training ($p > 0.05$), suffer from memory effects and the limited metacognitive abilities of children so are also not an ideal way to assess anxiety during the math task. As I discussed in chapter three, it is possible that the relationship between math anxiety and learning is more nuanced than being mainly driven by differences in cognitive load. In future work I aim to examine the relationship between gesture, math anxiety, and cognitive load in an adult learning paradigm using the same parasympathetic measure to try to address this puzzle.

In my final chapter I showed that children who undergo a lasting change in knowledge during training have a different parasympathetic signature than children whose knowledge is stable (giving consistently correct or incorrect answers) and from children who appear to learn but do not have that learning stick beyond training. My physiological results suggest that children who learn and keep that knowledge on the posttest may be more cognitively engaged during their insight moment. Rather than showing an increase in parasympathetic activity while writing their answers, learners show a consistent level of activity before and while writing their first correct solution. Moreover, it appears that this pattern of parasympathetic activity does not continue once they start solving problems correctly. Children who have a transient insight moment (i.e., they get one problem correct but then the following problems incorrect) appear to have a different pattern of parasympathetic activity from children who have true insight and from children who have stable knowledge (correct or incorrect) over time. My next step will be to look at changes in parasympathetic activity around the learning moment compared to changes in other parameters, such as children's facial expressions, low-level movement characteristics of how they produce their instructed gestures, and subtle changes in the prosody of their speech or word choice. By combining multiple measures, we may be able to identify or even predict a child's moment of insight and whether or not that knowledge will be lasting.

While my final chapter is less linked to cognitive load than the previous chapter, it may be that my observed differences between lasting and transient learners could be in part explained by a cognitive load account. For example, children who appear to learn and but immediately lose that knowledge have a large increase in parasympathetic activity right after coming up with the correct answer. We could interpret this change in RSA to reflect a decrease in cognitive load, which the children who learn and keep the knowledge do not show. This could suggest that staying cognitively engaged with the problem immediately after having an insight moment is associated with that learning sticking.

Overall this dissertation provides intriguing insights about gesture-speech mismatch, relations between spontaneous and instructed gesture on cognitive load, individual differences in learning from gesture, and a deeper understanding of mechanisms of cognitive change. Hopefully, this work will inspire other gesture researchers to apply psychophysiological tools to help elucidate mechanisms through which gesture reflects and changes knowledge.

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APPENDICES

Appendix A. Parent/Guardian Questionnaire

Theories of Intelligence Scale

This questionnaire has been designed to investigate ideas about intelligence. **There are no right or wrong answers.** We are interested in your ideas.

Using the scale below, please indicate the extent to which you agree or disagree with each of the following statements by writing the number that corresponds to your opinion in the space next to each statement.

1	2	3	4	5	6
Strongly Agree	Agree	Mostly Agree	Mostly Disagree	Disagree	Strongly Disagree

______. You have a certain amount of intelligence, and you can't really do much to change it.

______. Your intelligence is something about you that you can't change very much.

______. No matter who you are, you can significantly change your intelligence level.

______. To be honest, you can't really change how intelligent you are.

______. You can always substantially change how intelligent you are.

______. You can learn new things, but you can't really change your basic intelligence.

______. No matter how much intelligence you have, you can always change it quite a bit.

______. You can change even your basic intelligence level considerably.

Math Questionnaire

Using the scale below, please indicate the extent to which you agree or disagree with each of the following statements by writing the number that corresponds to your opinion in the space next to each statement. For the items referring to math classes and tests, please think back to when you were a student. *Note that the scale has changed from the last questionnaire:

1	2	3	4	5
Strongly Disagree	Disagree	Undecided	Agree	Strongly Agree

______. It wouldn't bother me at all to take more math classes.

______. I have usually been at ease during math tests.

______. I have usually been at ease in math courses.

______. I usually don't worry about my ability to solve math problems.

______. I almost never get uptight while taking math tests.

______. I get really uptight during math tests.

______. I get a sinking feeling when I think of trying hard math problems.

______. My mind goes blank and I am unable to think clearly when working mathematics.

______. Mathematics makes me feel uncomfortable and nervous.

______. Mathematics makes me feel uneasy and confused.

Demographic Questionnaire

The following information will give us a greater understanding of your child's background.

Your child may still participate in the study if you do not wish to provide this information.

1. What is your child's gender?
    a. Male
    b. Female
2. What is your child's date of birth (MM/DD/YYYY)? ___________________
3. What is your child's race?
    a. White
    b. Black
    c. Asian
    d. Native American
    e. Native Pacific Islander
    f. More than one race (please specify which ones): ________________
    g. Other (please specify): ___________________
4. What is your child's ethnicity?
    a. Hispanic
    b. Not Hispanic
    c. Unknown/unreported
5. How many family members live in your house? ______
    a. Please specify the relationship of these individuals to your child and the ages of any children (e.g., mother; sister, 7, etc.)________________________________
6. What is the primary language spoken at home? _____________________________

7. What is your child's native language? ____________________________

8. Please list any other languages that your child speaks _______________________

9. What grade in school is your child currently in? ___________________

10. What kind of school does your child go to?

    a. Chicago Public School

    b. Charter School

    c. Religious School

    d. Private School

    e. Other (please specify): ___________________________

11. What is the name of your child's school?

12. Please list any movement experience your child has (e.g., athletics, dance, martial arts, etc.) and how long your child practiced it.

    a. Experience 1: _____________________________ Number of months/years: _____

    b. Experience 2: _____________________________ Number of months/years: _____

    c. Experience 3: _____________________________ Number of months/years: _____

    d. Experience 4: _____________________________ Number of months/years: _____

    e. Experience 5: _____________________________ Number of months/years: _____

13. Outside of organized activities, how much does your child use his or her body?

    a. Almost never

    b. Rarely

    c. Somewhat often

    d. Often

    e. Very often (constantly moving, has trouble staying still)

14. How much experience does your child have playing video games?

    a. Low (rarely plays games)

    b. Medium (plays sometimes)

    c. High (plays often)

15. How much musical experience does your child have?

    a. None (never played a musical instrument)

    b. Some (took some lessons)

    c. Experienced (can play an instrument).

        i. Which instrument? ____________

16. Please specify:

    Mother's occupation: __________________________

    Father's occupation: ___________________________

17. Mother's highest level of education completed (circle one):

    a. Less than high school

    b. High school or GED

    c. Some college but no degree

    d. Associate's degree or equivalent 2-year undergraduate degree

        i. Type of degree (please specify): __________

        ii. Field of study (please specify): ___________

    e. Bachelor's degree or equivalent 4-year undergraduate degree

        i. Type of degree (please specify): __________

        ii. Field of study (please specify): ___________

    f. Some graduate training (not completed)

i. Type of degree (please specify): __________

ii. Field of study (please specify): ___________

g. Graduate degree

i. Type of degree (please specify): __________

ii. Field of study (please specify): ___________

18. Father's highest level of education attained (circle one):

a. Less than high school

b. High school or GED

c. Some college but no degree

d. Associate's degree or equivalent 2-year undergraduate degree

i. Type of degree (please specify): __________

ii. Field of study (please specify): ___________

e. Bachelor's degree or equivalent 4-year undergraduate degree

i. Type of degree (please specify): __________

ii. Field of study (please specify): ___________

f. Some graduate training (not completed)

i. Type of degree (please specify): __________

ii. Field of study (please specify): ___________

g. Graduate degree

i. Type of degree (please specify): __________

ii. Field of study (please specify): ___________

19. How much total combined money did all members of your HOUSEHOLD earn in 2017?

This includes money from jobs; net income from business, farm, or rent; pensions;

dividends; interest; social security payments; and any other money income received by members of your HOUSEHOLD that are EIGHTEEN (18) years of age or older. Please report the total amount of money earned - do not subtract the amount you paid in taxes or any deductions listed on your tax return.

a. Less than $20,000
b. $20,000 to $34,999
c. $35,000 to $49,999
d. $50,000 to $74,999
e. $75,000 to $99,999
f. $100,000 to $149,999
g. $150,000 or More

20. What is your race?

a. White
b. Black
c. Asian
d. Native American
e. Native Pacific Islander
f. More than one race (please specify which ones): ________________
g. Other (please specify): ___________________

21. What is your ethnicity?

a. Hispanic
b. Not Hispanic
c. Unknown/unreported

22. What is your native language? ____________________

23. How often do you talk with your child about math? (circle one)

1	2	3	4	5
Never	Rarely	Sometimes	Often	Very Often

24. How much do you agree or disagree with the following statements?

	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
I like math.	1	2	3	4	5
I am good at math.	1	2	3	4	5
My child likes math.	1	2	3	4	5
My child is good at math.	1	2	3	4	5

25. What is the average grade your child gets on mathematics assignments in school? ______

26. What is the average grade your child gets on assignments in school other than mathematics? _________

27. Please rate how anxious you think your child is in general

1	2	3	4	5
Not at all anxious	Not anxious	Somewhat anxious	Anxious	Very anxious

28. Please rate how anxious your child seems about each of the following subjects. Circle a number from 1 (not at all anxious) to 5 (very anxious) for each row.

	Not at all anxious	Not anxious	Somewhat anxious	Anxious	Very anxious
Mathematics	1	2	3	4	5
Reading	1	2	3	4	5
Writing	1	2	3	4	5
Science	1	2	3	4	5
Social Studies	1	2	3	4	5
Arts	1	2	3	4	5

29. What is your relation to your child?

a. Mother

b. Father

c. Other: ____________

Appendix B. Mathematical equivalence problems used in pretest, training, posttest, and generalization.

Pretest (used for half of participants for posttest, as has been done in previous studies using this paradigm to control for potential differences in problem difficulty)

5 + 8 + 2 = __ + 2
9 + 4 + 6 = __ + 6
7 + 5 + 8 = 7 + __
8 + 6 + 9 = 8 + __
3 + 4 + 5 = __ + 5
5 + 3 + 6 = 5 + __

Training

3 + 2 + 8 = __ + 8
4 + 5 + 7 = __ +
2 + 4 + 9 = __ + 9
5 + 2 + 6 = __ + 6
7 + 4 + 2 = __ + 2
6 + 2 + 5 = __ + 5

Posttest (used for half of participants for pretest)

3 + 7 + 5 = __ + 5
4 + 5 + 6 = __ + 6
8 + 4 + 3 = 8 + __
6 + 5 + 7 = 6 + __
4 + 7 + 9 = __ + 9
2 + 3 + 9 = 2 + __

Generalization Test

7 + 2 + 4 = __ + 3
5 + 3 + 7 = 4 + __
2 + __ = 2 + 8 + 5
__ + 7 = 3 + 9 + 7
4 + __ = 6 + 5 + 2
__ + 3 = 6 + 5 + 2

Appendix C. Protocol used by Experimenter 2 during Instruction and Training phases of the math equivalence paradigm.

This is from the Correct Gesture condition. The script for the Partially Correct Gesture condition was identical, except the experimenter consistently pointed to the second and third numbers (b and c). In the No Gesture condition, the experimenter just taught the words alone.

INSTRUCTION

Experimenter B enters the room. Experimenter A leaves the room and waits in hallway.

- **"Now we're going to practice some words and hand movements that will help you think about this problem. Let me show you a problem on the board."** *Write first problem on the board*

  1.) **6 + 3 + 4 = _ + 4**

- **Now I want you to listen to what I say and watch how I move my hands and see if you can copy after me.** *pause* **I want to make one side** *(RH V under 6 + 3)* **equal to the other side** *(RH point to blank)*. *pause*

- **Now can you stand on the line and say the words and do the hand movements just like I did?** *Move to left/backwards and ask child to stand on the line. Make sure you are not standing in line of the camera. Keep on that problem until the child says and gestures it, modeling again if necessary (up to 3 times).*

- **"I want you to remember those exact words and hand movements because I am going to ask you to say and do them sometimes in the next part. Let's try it again."** *Erase numbers and write next problem on the board*

  2.) **9 + 2 + 3 = _ + 3**

- **Now I want you to listen to what I say and watch how I move my hands and see if you can copy after me.** *pause* **I want to make one side** *(RH V under 9 + 2)* **equal to the other side** *(RH point to blank)***.** *Pause.* **Now can you say the words and do the hand movements to this problem?"** *Keep on that problem until the child says it, modeling again if necessary*
- **"I want you to remember those exact words and hand movements because I am going to ask you to say and do them sometimes in the next part. Let's try it one more time to be sure.** *Erase numbers and write next problem on the board*

  3.) **8 + 4 + 6 = _ + 6**
- **Now I want you to listen to what I say and watch how I move my hands and see if you can copy after me.** *pause* **I want to make one side** *(RH V under 8 + 4)* **equal to the other side** *(RH point to blank)***.** *pause* **Now can you say the words and do the hand movements to this problem?"** *Keep on that problem until the child says it, modeling again if necessary*
- **"Remember, I want you to remember those words and hand movements because I am going to ask you to say them sometimes in the next part. What we're going to do next is take turns solving problems, and sometimes I am going to ask you to say those exact words, and do those hand movements, OK?**

<u>TRAINING</u>

"First it's my turn". *(Experimenter never gestures in training)*

E1.) **5 + 6 + 3 = __ + 3**, *Write numbers and then <u>write 11 in the blank</u> and put marker on tray.*

"I want you to pay attention to how I explain this problem. "

"I want to make one side equal to the other side. See, 5 plus 6 plus 3 equals 14. And 11 plus 3 equals 14. So one side equals the other side. *(pause)* **Now it's your turn."**

C1.) **3 + 2 + 8 = __ + 8** *Write numbers on the board, put marker on tray, and step to left side so child can stand on line. Do not block cameras.*

"First can you say the words and do the hand movements exactly like we practiced?"

(child says words and gestures. OK to demonstrate gesture one final time if can't remember it)

"Next can you put your answer in the blank?

(child picks up the marker and writes in answer)

"Now can you say the words and do the hand movements again exactly like we practiced?

(child says words and gestures)

"OK, now it's my turn."

E2.) **9 + 3 + 4 = __ + 4**, *Write numbers and then* *<u>write 12 in the blank</u> and put marker on tray.*

"I want to make one side equal to the other side. See, 9 plus 3 plus 4 equals 16. And 12 plus 4 equals 16. So one side equals the other side. *(pause)* **Now it's your turn."**

C2.) **4 + 5 + 7 = __ + 7** *Write numbers on the board, put marker on tray, and step to left side so child can stand on line. Do not block cameras.*

“First can you say the words and do the hand movements exactly like we practiced?”

(child says words and gestures)

“Next can you put your answer in the blank?

(child picks up the marker and writes in answer)

“Now can you say the words and do the hand movements again exactly like we practiced?

(child says words and gestures)

“OK, now it’s my turn.”

E3.) **4 + 2 + 7 = __ + 7,** *Write numbers and the <u>write 6 in the blank</u> and put marker on tray.*

"I want to make one side equal to the other side. See, 4 plus 2 plus 7 equals 13. And 6 plus 7 equals 13. So one side equals the other side. *(pause)* **Now it's your turn."**

C3.) **2 + 4 + 9 = __ + 9** *Write numbers on the board, put marker on tray, and step to left side so child can stand on line. Do not block cameras.*

“First can you say the words and do the hand movements exactly like we practiced?”

(child says words and gestures)

“Next can you put your answer in the blank?

(child picks up the marker and writes in answer)

"Now can you say the words and do the hand movements again exactly like we practiced?

(child says words and gestures)

"OK, now it's my turn."

E4.) **7 + 2 + 5 = __ + 5,** *Write numbers and the write 9 in the blank and put marker on tray.*

"I want to make one side equal to the other side. See, 7 plus 2 plus 5 equals 14. And 9 plus 5 equals 14. So one side equals the other side. *(pause)* **Now it's your turn."**

C4.) **5 + 2 + 6 = __ + 6** *Write numbers on the board, put marker on tray, and step to left side so child can stand on line. Do not block cameras.*

"First can you say the words and do the hand movements exactly like we practiced?"

(child says words and gestures)

"Next can you put your answer in the blank?

(child picks up the marker and writes in answer)

"Now can you say the words and do the hand movements again exactly like we practiced?

(child says words and gestures)

"OK, now it's my turn."

E5.) **8 + 3 + 2 = __ + 2**, *Write numbers and the* *write 11 in the blank* *and put marker on tray.*

"I want to make one side equal to the other side. See, 8 plus 3 plus 2 equals 13. And 11 plus 2 equals 13. So one side equals the other side. *(pause)* **Now it's your turn."**

C5.) **7 + 4 + 2 = __ + 2** *Write numbers on the board, put marker on tray, and step to left side so child can stand on line. Do not block cameras.*

"First can you say the words and do the hand movements exactly like we practiced?"

(child says words and gestures)

"Next can you put your answer in the blank?

(child picks up the marker and writes in answer)

"Now can you say the words and do the hand movements again exactly like we practiced?

(child says words and gestures)

"OK, now it's my turn."

E6.) **5 + 3 + 2 = __ + 2**, *Write numbers and the* *write 8 in the blank* *and put marker on tray.*

"I want to make one side equal to the other side. See, 5 plus 3 plus 2 equals 10. And 8 plus 2 equals 10. So one side equals the other side. *(pause)* **Now it's your turn."**

C6.) **6 + 2 + 5 = __ + 5** *Write numbers on the board, put marker on tray, and step to left side so child can stand on line. Do not block cameras.*

“First can you say the words and do the hand movements exactly like we practiced?”

(child says words and gestures)

“Next can you put your answer in the blank?

(child picks up the marker and writes in answer)

“Now can you say the words and do the hand movements again exactly like we practiced?

(child says words and gestures)

Experimenter B leaves room and Experimenter A returns.

Appendix D. Math Task Questions

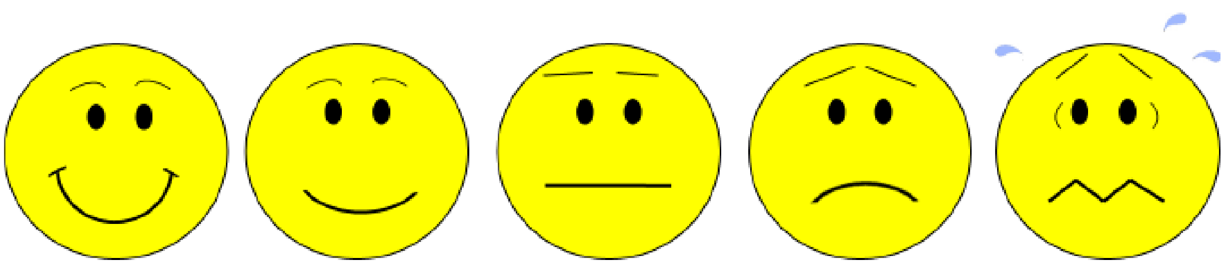
1. How much did you enjoy the exercise we just did?

I loved it | I liked it | It was ok | I didn't like it | I hated it

2. How confident did you feel when you were solving the first set of problems on paper?

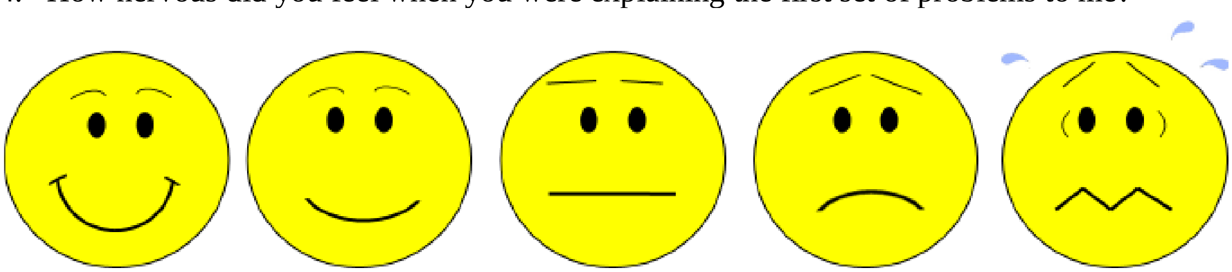
Very confident | Somewhat confident | Not sure | Not confident | Not confident at all
(I think I got them all right) | (I think I got some right) | (I think I got them all wrong)

3. How nervous did you feel when you were solving the first set of problems on paper?



Not nervous at all | A little nervous | Somewhat nervous | Very nervous | Very, very nervous

4. How nervous did you feel when you were explaining the first set of problems to me?

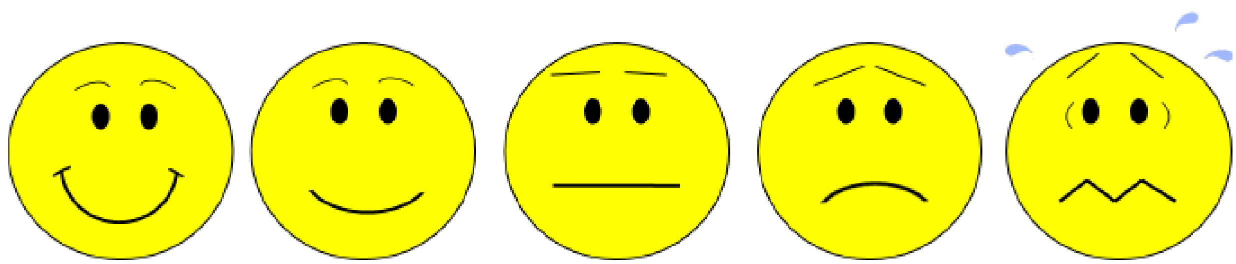


Not nervous at all | A little nervous | Somewhat nervous | Very nervous | Very, very nervous

5. How confident did you feel when you were solving problems with the other teacher?

Very confident	Somewhat confident	Not sure	Not confident	Not confident at all
(I think I got them all right)		(I think I got some right)		(I think I got them all wrong)

6. How nervous did you feel when you were solving problems with the other teacher?



Not nervous at all	A little nervous	Somewhat nervous	Very nervous	Very, very nervous

7. When you were solving problems on the board with the other teacher, how much did you care about whether or not you got the problems right?

1	2	3	4	5
Didn't care at all	Barely cared	Cared a little	Cared a lot	Really, really cared

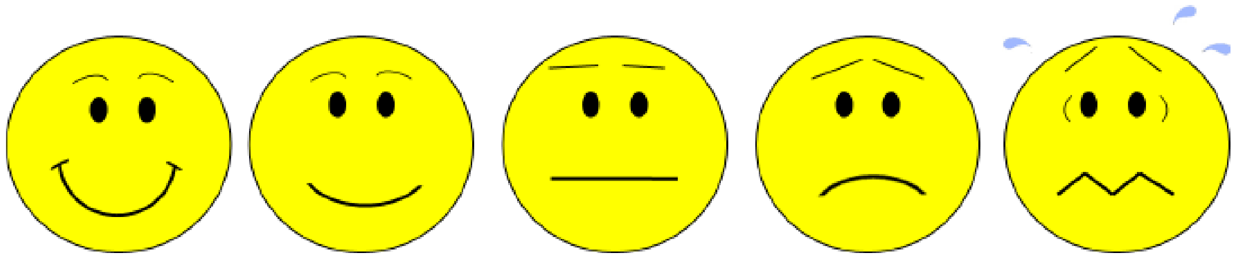
8. When you were solving problems on the board with the other teacher, how hard did you try to get the problems right?

1	2	3	4	5
Didn't try at all	Barely tried	Tried a little	Tried a lot	Really, really tried

9. How confident did you feel when you were solving the second to last set of problems on paper?

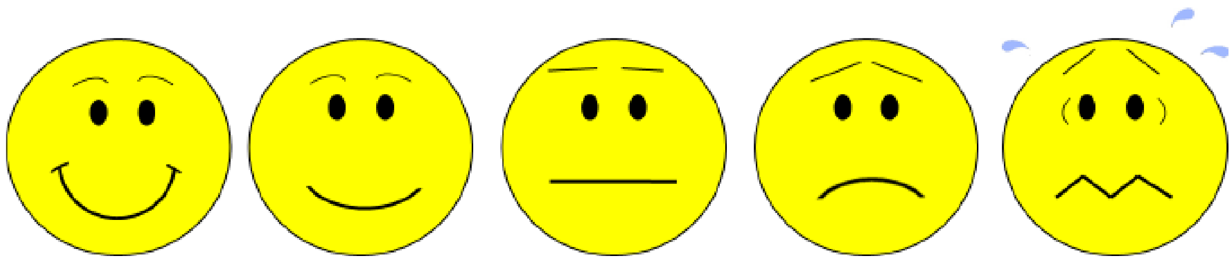
Very confident	Somewhat confident	Not sure	Not confident	Not confident at all
(I think I got them all right)		(I think I got some right)		(I think I got them all wrong)

10. How nervous did you feel when you were solving the second to last set of problems on paper?



Not nervous at all	A little nervous	Somewhat nervous	Very nervous	Very, very nervous

11. How nervous did you feel when you were explaining the second to last set of problems to me?

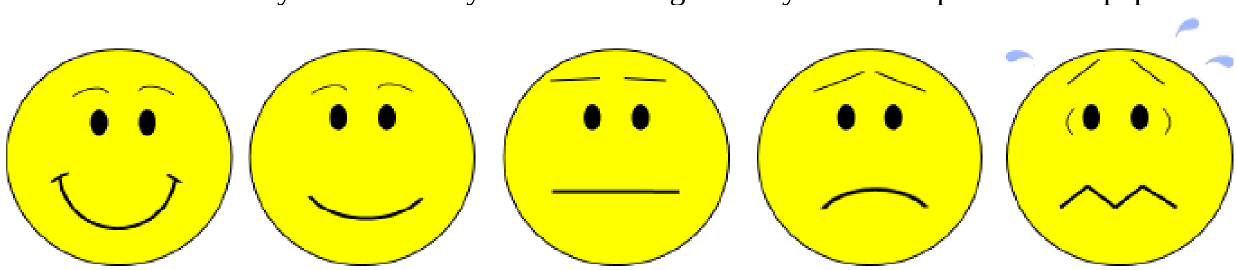


Not nervous at all	A little nervous	Somewhat nervous	Very nervous	Very, very nervous

12. How confident did you feel when you were solving the very last set of problems on paper?

Very confident	Somewhat confident	Not sure	Not confident	Not confident at all
(I think I got them all right)		(I think I got some right)		(I think I got them all wrong)

13. How nervous did you feel when you were solving the very last set of problems on paper?



Not nervous at all	A little nervous	Somewhat nervous	Very nervous	Very, very nervous

Appendix E. Math Competence Scale

How much do you agree or disagree with the following statements?

Work in mathematics is easy for me.

1	2	3	4	5
True	Mostly true	Sometimes false and sometimes true	Mostly false	False

I learn things quickly in mathematics.

1	2	3	4	5
True	Mostly true	Sometimes false and sometimes true	Mostly false	False

I am good at mathematics.

1	2	3	4	5
True	Mostly true	Sometimes false and sometimes true	Mostly false	False

I like mathematics.

1	2	3	4	5
True	Mostly true	Sometimes false and sometimes true	Mostly false	False

I look forward to mathematics.

1	2	3	4	5
True	Mostly true	Sometimes false and sometimes true	Mostly false	False

I am interested in mathematics.

1	2	3	4	5
True	Mostly true	Sometimes false and sometimes true	Mostly false	False

I try to solve even very hard math tasks.

1	2	3	4	5
True	Mostly true	Sometimes false and sometimes true	Mostly false	False

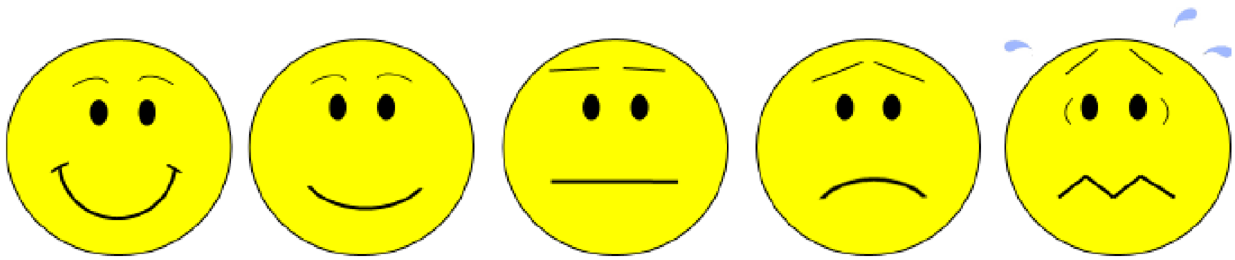
I try my best at math.

1	2	3	4	5
True	Mostly true	Sometimes false and sometimes true	Mostly false	False

I look forward to unfamiliar math tasks.

1	2	3	4	5
True	Mostly true	Sometimes false and sometimes true	Mostly false	False

Appendix F. Scale for Early Math Anxiety



1	2	3	4	5
Not nervous at all	A little nervous	Somewhat nervous	Very nervous	Very, very nervous

<u>Math Facts</u>

Practice. Who's the President of the United States?
1. George bought two pizzas that had six slices each. How many total slices did George have to share?
2. Is this right? 9 + 7 = 18.
3. How much money does Annie have if she has two dimes and four pennies?
4. How do you write the number *four hundred and eighty two*?
5. Draw an hour and minute hand on a clock so that it would read 3:15 PM.
6. Draw a triangle and a square on the board.
7. Count aloud by 5 s from 10 to 55.
8. What time will it be in 20 min?
9. Is this right? 15−7 = 8?
10. Daisy has more money than Ernie. Ernie has more money than Francesca. Who has more money?

<u>Math Situations</u>

Practice. You're about to ride a roller coaster.
1. You are in math class and your teacher is about to teach something new.
2. You have to sit down to start your math homework.
3. You are adding up all the money in your piggy bank.
4. Someone asked you to cut up an apple pie into four equal parts.
5. You are about to take a math test.
6. You are in math class and you do not understand something. You ask your teacher to help you.
7. Your teacher gives you a bunch of addition problems to work on.
8. Your teacher gives you a bunch of subtraction problems to work on.
9. You are in class doing a math problem on the board.
10. You are listening as your teacher explains to you how to do a math problem.