What the Hands Tell Us About Mathematical Learning: A Synthesis of Gesture Use in Mathematics Instruction

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Abstract

Mathematical achievement is an early predictor of students' academic outcomes, and mathematics achievement continues to be important throughout life. Thus, it is essential to examine instructional methods that enhance mathematical learning. One method that may impact mathematical learning is the use of gestures, yet a comprehensive methodical review of the data has not been conducted. The current study examined the impact that gestures have on student learning when educators use gestures during mathematical instruction and educators' perception of student mathematical knowledge when students use gestures. A systematic search was conducted to assemble research studies that evaluated the use of gestures in mathematical instruction with students in preschool to 12th grade. Empirical data from 35 research articles indicate that gestures used by students or educators that enhance verbal instruction can increase student mathematical performance and memory. Furthermore, it is practical to teach students and educators to use gestures effectively during mathematical learning.

Keywords: mathematics; gestures; instruction; teaching

What the Hands Tell Us About Mathematical Learning: A Synthesis of Gesture Use in Mathematics Instruction

Across the elementary and secondary grade levels, students are expected to learn mathematics across a variety of domains, such as place value, fractions, measurement, geometry, and algebra. The complexity of mathematics can place a strain on the cognitive load of students, making it difficult for students to understand and master different mathematical concepts. Therefore, it is vital that educators provide appropriate access to mathematics by using techniques that enhance mathematical learning for all students across all levels of achievement. In this manuscript, we synthesize the research on one technique – gestures – to understand how educators and students use and learn from gestures in the area of mathematics.

Mathematics

Mathematics is a cumulative discipline, which becomes increasing more complex across the grade levels, linking new concepts with previous learned material (National Governors Association Center for Best Practices & Council of Chief State School Officers, 2010). For example, addition concepts learned in kindergarten with adding two and three, transition to addition with sums to 20 in first grade and addition of multi-digit numbers in second and third grade. Knowledge of addition helps with understanding of multiplication in third, adding of fractions in fourth grade and fifth grade, and adding of decimals in fifth and sixth grade. In the middle school grades, addition knowledge is applied to add positive and negative integers, interpret expressions, or solve equations. Without a strong understanding of the concept of addition, many of these tasks would become increasingly difficult for students. When considering the cumulative nature of mathematics, researchers have demonstrated that lower early academic performance in mathematics impacts students' academic outcomes in later grades (Rittle-Johnson, Fyfe, Hofer, & Farran, 2017) and throughout life (Ritchie & Bates, 2013). In fact, mathematics performance in school is a stronger predictor of adulthood income levels than reading performance (Dougherty, 2003).

For students, understanding mathematics involves learning about concepts; developing fluency with procedures; representing and solving problem; being able to reflect, explain, and justify reasoning; and seeing mathematics as worthwhile and useful (Kilpatrick, Swafford, & Findell, 2001). To improve student knowledge of mathematics, educators should engage with mathematical practices that help students understand mathematics (National Governors Association Center for Best Practices & Council of Chief State School Officers, 2010). One instructional technique that could be used by educators to increase student knowledge of mathematics across the continuum of mathematics is the use of gestures. Gestures could also be used by students to communicate mathematical ideas and make sense of mathematics. In the next section, we provide an overview of gesture use by educators and students and how gestures may be especially important in the teaching and learning of mathematics.

Gestures

A gesture is typically defined as a movement or movements of the body (e.g., hands, arms, head) that help show meaning. Very young children (i.e., infants and toddlers) use gestures to communicate needs and wants before speech is available as a tool for communication (Child, Theakston, & Pika, 2014; Zampini et al., 2016). For example, infants may use gesture to indicate that they want something, like a toy (Olson & Masur, 2015). In preschool, students may continue to use gestures for communication of needs and wants (Cochet, Centelles, Jover, Plachta, & Vauclair, 2015) along with other gestures that are tied to speech and language (e.g., a waving hand meaning "bye-bye"). Young students may also use gestures to communicate thoughts or feelings (Novack & Goldin-Meadow, 2015), and many student gestures can provide insight as to what students understand (Goldin-Meadow, 2004).

Using gestures for communication may not only be a tool that is utilized by children. Caregivers and educators may use gestures to communicate with young children and help young children learn. For example, gestures can act as cues for helping students to remember something or to do something (Sekine, 2011). Gestures can also help a student focus on a task. Related to academics, gestures can be used by adults to help young children remember stories (Cameron & Xu, 2011) or to develop vocabulary (de Nooijer, van Gog, Paas, & Zwaan, 2014). As described by Congdon et al. (2017), gestures are most effective for students when educators pair gestures simultaneously with spoken language.

In this synthesis, we analyzed how educators and students used gestures within the teaching or learning of mathematics. The connection between gestures and mathematics is natural for several reasons. First, strong mathematics teaching utilizes multiple modes of interaction with mathematics content. Bruner (1966) described mathematics teaching and learning as occurring in three modes - the enactive, iconic, and symbolic. That is, educators should help students learn mathematics through enactive activities (e.g., hands-on mathematics experiences) and with iconic representations (i.e., drawings) so to help students understand the symbolic form of mathematics (i.e., mathematics with numbers, symbols, and words). Hands-on activities and iconic representations may cause educators or students to use planned or spontaneous gestures, which may allow students to develop a deeper knowledge of mathematics concepts and procedures. For example, when using a number line to discuss subtraction as comparison, it would be helpful to use gestures combined with speech (e.g., a finger on 9, another finger on 4, and discussion about how to determine the difference between the two numbers) rather than trying to describe the difference between 9 and 4 with speech alone. Gestures may also function as an enactive activity or iconic representative form themselves (Lakoff & Núñez, 2000). Second, gestures can help provide meaning to the language of mathematics. As mathematics has its own language and utilizes many general English words in different ways (Rubenstein & Thompson, 2002), it is vital that educators provide focused instruction on the language of mathematics (Schleppegrell, 2012). Gestures could help students understand the vocabulary (i.e., language) of mathematics for terms such as *addition*, *difference*, *equal*, *perimeter*, or *zero pairs*. Gestures could also be used by students to communicate within the language of mathematics.

Research indicates that gestures, when used by educators during mathematics instruction, can substantially impact learning when used simultaneously with speech to link new mathematical ideas with previously learned material (Alibali et al., 2014). Importantly, the use of gestures during mathematics instruction may reduce the cognitive load for students to make mathematics learning easier (Alibali et al., 2014; Cook, Yip, & Goldin-Meadow, 2012; Goldin-Meadow, Nusbaum, Kelly, & Wagner, 2001). This may be especially important if students experience difficulty with the language of mathematics or as students demonstrate a lack of proficiency in mathematics. In many studies, students who received mathematics instruction accompanied by gestures, performed better on mathematics and memory-based tasks compared to students that received instruction without the use of gestures (Cook, Duffy, & Fenn, 2013; Cook, Mitchell, & Goldin-Meadow, 2008; Francaviglia & Servidio, 2011; Goldin-Meadow, Kim, & Singer, 1999).

Conversely, research on the use of gestures has not always demonstrated a positive impact on mathematical learning (Congdon, Kwon, & Levine, 2018). For example, Nicoladis, Pika, and Marentette (2010) determined that preschool students counted more accurately when mapping number words to counts than number gestures onto objects, which suggested that the use of number gestures may not help students map symbols to numbers words. Therefore, research investigating the impact of gestures on mathematical learning may be inconsistent or may be different based on mathematical content. This necessitates the examination and synthesis of the literature, and this is the purpose of conducting this synthesis.

Purpose and Research Questions

To understand the body of literature related to gestures and the use of gestures within mathematics teaching and learning, we conducted a synthesis on the gestural literature. We examined both educator and student gestures, to summarize the general themes of the use and impact of gestures in mathematics. Specifically, we asked two questions about the educator use of gestures and two questions about the student use of gestures:

1. How do educators use gestures to instruct students in mathematics?
2. What impact do gestures have on student performance when educators use gestures during mathematics instruction?
3. How do students use gestures during mathematics instruction?

4. Does student performance increase when students gesture?

Method

This synthesis involved a systematic analysis of studies focused on the use of gestures by educators and students within the context of mathematics. We examined and summarized each study that met inclusion criteria in terms of participants, use of gestures, and results. Given our aim to examine all available empirical research, various research methodologies are included in this synthesis (e.g., randomized controlled trials, correlational, descriptive narratives, etc.).

Systematic Search Procedures

A three-stage search was used to identify relevant items pertaining to this review. The first stage included a search within the electronic databases of Academic Search Complete, Education Resources Information Center (ERIC), Education Source, and PsycINFO with the following search terms: line 1 subject terms: *math**; line 2 subject terms: *gesture* OR movement OR nonverbal*; and line 3 subject terms NOT: *deaf OR hear**. Limits were set to only peer-reviewed articles within a 30-year span of January 1986 to February 2016.

The second stage of the search entailed a targeted search of articles published by two research groups. A notable amount of gesture research came from Martha Alibali and Susan Goldin-Meadow. Thus, a targeted search was conducted focusing on these two scholars to ensure all studies by their teams were captured.

In the third stage, a hand search was conducted using the journals in which the studies selected for the synthesis were published. Additionally, we looked at journals in which were cited most often within the studies. In all, we identified 3,313 articles in the electronic databases, targeted author search, and hand search. After we removed duplicates, 2,180 articles remained. The first two authors read titles and abstracts and determined whether studies met inclusion criteria.

Inclusion and Exclusion Criteria

After completion of the systematic search, we included articles if the study met the following criteria:

1. Article was published between January 1986 and February 2016.
2. Student participants were in preschool through 12th grade.
3. The content included mathematics and examined the use of gestures within teaching and learning.
4. The study was published in English or translated into English.

Studies that examined any body movements (i.e., hands, arms, head) that helped illustrate or portray mathematical content were eligible for inclusion. This encompassed traditional and nontraditional gestures (e.g. touching and pointing). Studies were excluded if participants were determined to be deaf and hard of hearing or blind and visually impaired. The use of gestures had to be naturally occurring during mathematics instruction or specific to mathematics content. If the study utilized American Sign Language (ASL) as a form of gesture, it was excluded (e.g., specific mathematics terms were translated to ASL to accompany the speech; Wilson, 2012). We also excluded studies in which educators acted as students with other educators (e.g., educators practiced graphing lessons; Arzarello, Robutti, & Thomas, 2015). Arzarello et al. (2015), however, included three case studies, in which we will report the findings from two of the cases that met inclusion criteria. Altogether, we identified 49 potential articles as matching inclusion criterion. The 49 articles were divided between the two researchers for further coding.

Coding Procedures

We used a coding procedure to organize information from each of the studies, with coding sheets developed by the research team. The first and second authors recorded information about the study characteristics, including: participant information, sample size, type of design, treatment and comparison group, descriptive narrative summary, location of study (e.g., one-on-one separate setting, general education classroom, special education resource room, or separate small group), mathematics content, and results on the coding sheet. We coded student and educator information using open-ended items (e.g., grade or age of subjects, exceptionality of subjects, number of students for each grade level). We obtained study design information using forced-choice and open-ended items, such as: type of design, fidelity checks, selection of participants, outcome measures, who was observed, implementer, session, length, duration of intervention or data collection, and description of gesture. We determined the use of the gestures by further coding each study with forced-choice and open-ended questions, which included: method (e.g. naturalistic or scripted), measure (e.g. frequency count, function, descriptive narrative), coding of gestures, description, and data.

The first and second authors received training on coding procedures by the third author and reliability was established by double coding until reliability reached 95% with three selected articles. Two researchers coded the 49 articles and determined that 14 articles did not fit eligibility criteria due to: (a) the gestures in the study were mathematical American Sign Language signs, which is considered another language; (b) the manner in which authors describe and analyzed gestures did not provide information related to our research questions; or (c) the article was a practitioner piece. The remaining 35 research articles were further analyzed. 70% of the 35 articles were double coded by the third researcher. Coded items were categorized as a match or mismatch across the two coders. Reliability was established by dividing the number of match items by the total number of coded items. All mismatch items were discussed among the coders, until an agreement was made. The reliability of the articles was 95.5%.

Results

The synthesis included a total of 35 research articles, which consisted of 16 studies within 14 qualitative research articles and 22 studies within 21 quantitative research articles. For the rest of this manuscript, we refer to the 16 qualitative studies as narratives because the information about gestures was provided in narrative form. We evaluated the 22 quantitative studies based on the data provided within each of the studies. Some studies provided frequency counts of the occurrences of gesture use by educators or students and other studies conducted correlational or experimental work in which researchers assigned educators or students to different conditions and had assigned levels of gesture use. See Table 1 for a brief, descriptive overview of all studies included in the synthesis.

Study Types

Narratives. Overall, 14 articles examined the use of gestures while learning and teaching mathematics using descriptive narratives. We defined descriptive narratives as studies that included a description of how gestures were used by educators and students without the presentation of quantitative data to describe the impact of the use of gestures. Note that Gerofsky (2010) reported the results of two separate studies within one article. We distinguished the studies within both articles by using “study 1” and “study 2” as descriptors. Of the descriptive narratives (*k* = 16), nine studies observed gestures as a strategy for learning (i.e., a way for learning about mathematics) and seven studies observed the use of gestures as a tool for communication of mathematical understanding (i.e., communicating about mathematics). In each study, the in-depth narratives provided by the authors described the use of gestures and the role they play in learning mathematics. The descriptive narrative studies are summarized in Table 2.

Frequency and correlational studies. In all, nine studies examined the use of gestures during mathematics instruction and provided descriptions and frequency counts of the gestures. Four studies observed the use of gestures by educators during mathematics instruction, and seven studies observed student use of gestures during mathematics learning (see Table 3). Note that two studies observed gestures by both educators and students (Goldin-Meadow et al., 1999; Goldin-Meadow & Singer, 2003). In each study, gesture was the dependent variable, and the authors often provided rich descriptions or operational definitions of the gestures, as seen in Table 3. In addition, two studies were classified as correlational, because group comparisons were conducted with students based on whether they gestured or not or on their identification of a specific disability (Alibali & Goldin-Meadow, 1993; Mainela-Arnold, Alibali, Ryan, & Evans, 2011). Table 3 provides a description of these studies.

Experimental studies. Overall, nine studies examined the use of gestures using experimental methodology. All of studies observed gestures use in students and one study observed gestures in both educators and students (Alibali et al., 2013). In most of the studies, gesture was often manipulated and acted as the independent variable. There were two studies, however, that used gestures as both the dependent and independent variable

(Alibali et al., 2013; Broaders, Cook, Mitchell, & Goldin-Meadow, 2007) and one study measured gestures as the dependent variable (Mainela-Arnold, Alibali, Ryan, & Evans, 2011). Table 3 provides a complete description of studies.

Educators Use of Gestures to Teach Mathematics

Educators inherently gestured while teaching mathematics to elementary and middle school students (Alibali et al., 2014; Flevares & Perry, 2001; Goldin-Meadow et al., 1999). That is, educators naturally gesture without prior preparation or intention to use gestures during mathematic instruction. Within the literature, three general themes of how educators applied gestures to their mathematic instruction emerged. First, educators utilized gestures more than other non-verbal representation modalities (i.e., pictures, concrete objects, written symbols). For example, Flevares and Perry (2001) observed three first-grade educators (experience ranged from 3 to 26 years) in an urban elementary school. Non-verbal symbolic number representations were coded in the videos as pictorial (i.e., drawing items or displayed drawn items), concrete objects (i.e., use of cubes or other manipulatives), written symbols (i.e., writing a number or displaying a number), or gestures. Gestures were defined as pointing to another representation type (e.g., picture, concrete object, or written symbol) or as a symbolic gesture, which included finger counting or using hands to indicate grouping of items being counted (see Table 3). Although there were individual differences across the different educators, all educators conveyed information using mathematically related gestures more than the other three representation modalities (i.e., pictures, concrete objects, written symbols). The educators also presented the majority of content using more than one numerical representation (e.g., holding up five fingers and pointing to five objects), and these combinations of representations almost always included a mathematical gesture.

Second, educators' gestures reinforced speech during mathematic instruction. Goldin-Meadow et al. (1999) recruited eight educators that either were currently or had formally taught mathematics or science in the elementary or secondary level. The mean of educator experience was 9.6 years and varied substantially (range = 1-33 years). Each educator was recorded while he or she provided mathematical equivalence instruction to third- and fourth-grade students in groups of 5 to 7 students. To reduce experimenter bias, the focus of the study (i.e., gestures) was not provided to the educators. During mathematics instruction, researchers observed educators to express a large portion of problem-solving strategies nonverbally, as gestures. Further, the use of mathematical gestures generally reinforced speech by conveying the same type of strategy.

Finally, educators tend to gesture more when new mathematic material was presented compared to concepts that have previously been presented to students. Alibali and colleagues (2014) observed use of gestures in six middle school educators. Researchers identified gestures by type (i.e., pointing, depictive, beat, or writing), classified as a linking (i.e., related to speech) or non-linking episode, and categorized as sequential or simultaneous, in relation to spoken instruction (see Table 3 for description). When linking concepts in speech and gesture, all of the middle school educators used sequential gestures more often than simultaneous gestures. That is, educators would often exhibit a depicted representation of their speech after rather than during their dialogue. Educators also gestured at a higher rate for speech and gesture links that involved new mathematical material than review material.

In sum, across these studies, educators naturally used gestures when teaching students mathematics (Alibali et al., 2014; Flevares & Perry, 2001; Goldin-Meadow et al., 1999), sometimes more than other mathematical representations (Goldin-Meadow et al., 1999), and when new material was presented to students (Alibali et al., 2014). Further, the use of mathematical gestures generally corresponded to the educators' verbal instruction (Flevares & Perry, 2001; Goldin-Meadow et al., 1999).

Impact of the Use of Gestures by Educators

All of the studies that examined gestures in mathematics determined that students performed higher when educators integrated gestures into mathematic instruction compared no gestures present during instruction (Alibali et al., 2013; Cook et al., 2013; Goldin-Meadow et al., 1999; Singer & Goldin-Meadow, 2005). Goldin-Meadow and colleagues (1999) measured student understanding of mathematical equivalence problems when educators used mathematical gestures during instruction compared to the absence of gestures. Students (M age = 9 years, 10 months) received instruction outside of their normal mathematics block for approximately 12 min (range = 5-16 min). Students understood mathematical strategies better when speech about equivalence was accompanied with matching mathematical gestures. Students also translated educators' gestures, which were not accompanied with speech, into verbal explanations of a mathematical strategy. Thus, students interpreted and understood mathematics instruction that included gestures, even in the absence of verbal instruction.

Use of gestures during mathematical instruction was also found to enhance transfer and retention of mathematical content. Cook et al. (2013) assigned students in second, third, and fourth grade to a speech-alone condition or a gesture and speech condition. Educators provided video instruction about mathematical equivalence problems using gesture and verbal instructions or verbal instructions only. Students performed better on addition mathematical equivalence at posttest and on a transfer test when in the speech and gesture condition than the speech-alone condition. Thus, students retained mathematics information better when gestures were used during mathematics instruction (Cook et al., 2013).

Importantly, how gestures are integrated into mathematical instruction is also important to students' mathematical performance. Singer and Goldin-Meadow (2005) assigned third and fourth graders to conditions in which gestures matched spoken strategy, gestures did not match spoken strategies, or no gestures were used while solving mathematical equivalence problems. Students performed better when they used gestures, but only when gestures conveyed a different strategy than speech. This indicated that the educator's gestures during mathematics instruction enhanced mathematical performance when it provided additional information to the verbal instruction.

The mathematic gesture research also indicated that educators can be taught to effectively integrate gestures into mathematics instruction. For example, Alibali and colleagues (2013) provided training to an educator on how to appropriately utilize gestures to link concepts during mathematics instruction. After the training, the educator increased the frequency of gesture use to link ideas in mathematics instruction. The types of gestures used by the educator are described Table 3. In the same study, seventh graders were randomly assigned to receive mathematics instruction covering graph and equations either before (i.e., control group) or after (i.e., enhanced-gesture group) the educator gesture training. There was a group difference for understanding graph and equations on the posttest. Specifically, students had greater gains in the enhanced-gesture condition than the control condition for understanding of intercept. Thus, gestures enhanced mathematical performance in students when used appropriately. Further, Alibali and colleagues (2013) indicated that educators could be trained to effectively use gestures during mathematics instruction.

Across the studies, students' performance in mathematics increased when educators incorporated gestures into their mathematics instruction; especially, when the gestures provided additional mathematical information than verbal instruction (Singer & Goldin-Meadow, 2005). However, the majority of these studies consisted of elementary students learning mathematical equivalence (Cook et al., 2013; Goldin-Meadow et al., 1999; Singer & Goldin-Meadow, 2005). There was only one study that examined a different grade level and mathematical content area (i.e., graphing in middle school students; Alibali et al., 2013). Thus, it is unclear if these findings can be generalized beyond elementary students and mathematical equivalence problems.

Student Use of Gestures During Mathematics Instruction

As seen with educators during mathematics instruction, students also naturally gestured while learning mathematics (Arzarello, Paola, Robutti, & Sabena, 2009; Arzarello et al., 2015; Bjuland, Certari, & Borgersen, 2008; Francaviglia & Servidio, 2011; Graham, 1999; Gerosky, 2010; Kim, Roth, & Thom, 2011; Logan, Lowrie, & Diezmann, 2014; Radford 2009). Across the studies, students gestured to learn mathematical concepts and to communicate their understanding. Students also tended to gesture more when mathematical concepts were new or challenging (Graham, 1999; Kim et al., 2011; Logan et al., 2014).

Learning gestures. We categorized gestures used by the students to aid in the learning of new concepts as *learning gestures*. Five of the studies observed the use of gestures to learn mathematical solutions within a unit about graphing with students in sixth through 11th grade (Arzarello et al., 2009; Arzarello et al., 2015; Bjuland et al., 2008; Radford 2009), one study examined preschool students counting objects (Arzarello et al., 2015), another study observed kindergarteners in a unit about geometry shapes and numeracy (Warren, Miller, & Cooper, 2013), and a final study observed seventh-grade students working on calculation of fractions (Zurina & Williams, 2011).

Within learning gestures, graphing was the most prominent mathematical topic. Bjuland et al. (2008) observed two small groups of sixth-grade students use gestures to illustrate the reasoning strategies necessary to make sense of a problem-solving task involving graphs and pictorial representations included within the graph. Researchers coded gestures by six types of pointing: repeated pointing (i.e., repeatedly points to the same object), consecutive pointing (i.e., points to different objects, one after the other), held-point (i.e., pointing to one object for 3 s or more), point-slide (i.e., points and moves finger or hand continuously between two objects), linear point-slide (i.e., points and move along a line between two objects), and circular point-slide (i.e., points and moves in a circular motion between two objects). All students made pointing and sliding gestures, but the most prominent gestures were consecutive pointing and held-point. Consecutive pointing indicated a relationship between the figures and diagrams to show a connection between the two representations, and a held-point gesture was a way to indicate attention to a particular object within the task.

The remaining three graphing studies observed 10th and 11th graders who graphed time and speed with calculators. As students moved toward understanding the meaning of concepts, students used spoken words, gestures (i.e., hand movements), body actions (i.e., body movements not specific to hands), objects, and mathematical signs in conjunction with one another to reach objectification (i.e., develop the meaning of abstract mathematical concepts into concrete understanding; Radford, 2009). As the students became more familiar with the concepts, body actions decreased while gestures and language became more relevant to their learning. Additionally, Arzarello et al. (2009) and Arzarello et al.'s (2015) study 2 provided case studies in which students sketched the graphs of a slope on paper with the assistance of a calculator. Note that Azzarello et. al. (2009, 2015) referred to gestures as "signs," however these studies were included because the description of signs matched our gesture inclusion criteria. Arzarello categorized gestures as falling into one of two categories: institutional (mathematical), if it was established by an institution or school, or personal, if it was an idiosyncratic production by the person. Researchers analyzed two case studies of 11th-grade students who independently completed tasks related to calculus graphing. Observations from both studies reported consistent findings: students exhibited predominantly iconic gestures (i.e., gestures that portrayed visual illustration of the concept) in order to support the explanation of words used to describe the size of the two distances (Arzarello et al., 2009; Arzarello et al., 2015). Thus, as the student's understanding of the mathematical content develops, their gesture evolves to reflect their mastery level (Arzarello et al., 2015).

The remaining studies that observed students using gestures for learning purposes ranged from preschool to seventh grade. For example, Arzarello et al.'s (2015) study 1 focused on student gestures when students counted three objects. The students moved from concrete pointing for one-to-one correspondence to abstract gestures that were representation of numbers (Arzarello et al., 2015). This study illustrates how students' use of gestures evolved, corresponding to their level of understanding of the mathematical content. Warren and colleagues (2013) implemented activities related to language, geometry, and number with kindergarten students on an individual basis and observed their responses. At the beginning of the lesson, students performed gestures along with the researcher, then, as students gained understanding of gestures and self-talk, students became more refined and no longer required the researcher's guidance (Warren et al., 2013). Students engaged in gestures and self-talk (i.e., think alouds) in conjunction with their thinking as a way to bridge the gap between learning and conceptual understanding of mathematics (i.e., shapes and computation). In the final study, Zurina and Williams (2011) observed seventh-grade students learning fractions and how gestures provided the students with a visual representation of the content, similar to Arzarello et al. (2015). For example, one way a student represented the fraction two-thirds with the following gestures; three-stroke chopping motion, a 'scissor' sign with two fingers, followed by a two-stroke chop. (Zurina & Williams, 2011). Gestures accompanied by words helped the students to visualize the concept of fractions and develop a concrete understanding of the mathematical content (Zurina & Williams, 2011).

In sum, students integrated gestures into their mathematical learning in preschool, kindergarten, middle school, and high school (Arzarello et al., 2009; Arzarello et al., 2015; Bjuland et al., 2008; Radford 2009; Warren, et al., 2013; Zurina & Williams, 2011). Further, students' gestures evolved as they learned and understood mathematical content (Arzarello et al., 2009; Arzarello et al., 2015; Radford 2009).

Communicative gestures. We categorized *communicative gestures* as those in which the students or educators used gestures to communicate concepts or further illustrate verbalizations. Three studies focused on students learning English (i.e., English Learners or ELs) and the way in which gestures built a foundation for concepts while learning mathematics (Domínguez, 2005; Rosborough, 2014; Shein, 2012). For example, Domínguez (2005) observed the use of gestures with second-grade bilingual students who communicated their mathematical thinking in both Spanish and English. This was the only study in which gestures operated under both learning and communication. The observations suggested that students used gestures to organize their own cognitive activity. When students completed mental operations or methods that inhibited gestures (i.e., calculator standard algorithm), fewer gestures were expressed. Students developed their own systems for keeping track of counted numbers by creating a hand gesture to indicate, "putting away 10 counted numbers" (p. 279) for learning of addition and subtraction computation (Domínguez, 2005). Researchers observed communication gestures performed by students such as; a sweeping hand gesture to indicate the total problem, a point gesture to numbers on chart when unable to recall the name of numbers, and drew the shape of a square in the air to represent hundreds chart when did not know the name of item.

Rosborough (2014) observed an educator who encouraged EL students to use their fingers as a form of gesture to represent numbers and quantity. Gestures acted as a mediation tool for students learning a second language. That is, students' mathematical thinking was transformed into gestures as a way to construct internal meaning. In this way, the educator and the student used gestures as a means to construct meaning of numeracy in English (Rosborough, 2014). Lastly, Shein (2012) examined the use of gestures and interaction between the fifth-grade ELs and an educator. The educator focused on the student's portrayal of their understanding on the meaning of the words associated with area of geometric shapes through gestures rather on than on the formal technical terms. For example, when the student used the word *straight*, she showed that she understood the *vertical height* through the use of an up-and down gesture (Shein, 2012). Across all three studies, not only did ELs use gestures to develop cognitive connections, they also utilized gestures to support their communication of mathematical knowledge. ELs used gestures to fill in the words or concepts they were not as confident in speaking to demonstrate their understanding (Domínguez, 2005; Rosborough, 2014; Shein, 2012).

Similar findings were found for students with language deficits. For example, Mainela-Arnold and colleagues (2011) measured mathematical equivalence strategies in third- through fifth-grade students identified with expressive Specific Language Impairment (SLI) expressive and receptive SLI, or typical-developing. Overall, students identified with SLI demonstrated delays in their knowledge of mathematical equivalence compared to typically developing peers. In addition, compared to the other groups, students identified with expressive and receptive SLI exhibited more incorrect strategies for solving the mathematical equivalence problems in both their speech and gestures. Students identified with expressive SLI exhibited correct strategies in gestures, however, these students often expressed the incorrect strategies in speech. The researchers concluded that students identified with expressive SLI depicted knowledge in gesture but not speech, student knowledge of mathematical equivalence may be represented in a non-verbal structure.

Two additional studies focused on the use of communication gestures within the topic of graphing (Botzer & Yerushalmy, 2008; Reynolds & Reeves, 2001). Reynolds and Reeves (2001) examined the relationship between eighth- and ninth-grade student gestures during two separate discussions of graphs. The students frequently illustrated a ball's movement on the graphs by use of gestures in a horizontal motion. In another situation, when the student was uncertain, she exhibited more gestures in place of the spoken language as a way to further her explanation. Researchers determined that gestures to have two main communication purposes for students. First, students used gestures to maintain and refocus joint attention to the problem at hand. Second, gestures tended to act as an amplifier of speech in order to establish and extend meaning of unfamiliar content (Reynolds & Reeves, 2001). Similarly, Botzer and Yerushalmy (2008) observed 11th- and 12th-grade students in a technology-based setting that allowed students the opportunity to produce and interpret graphs in a two-dimensional motion in a plane. Gestures played an integral role in communication between the students and enabled students to share the information embedded in the graphs. Gestures mediated the production of socially constructed meaning for the motion of the graph. For example, students used gestures to represent the slope of a graph and identified zero slope with zero velocity. Gestures also accompanied the oral elaboration of the meaning of graphic signs. Students represented physical features of the motion by gestures and related them to mathematical features of the graphs (Botzer & Yerushalmy, 2008).

To further demonstrate the use of gestures as a form of communication, Elia and colleagues (2014) explored the connection between language and gestures with kindergarteners and their explanation of geometric shapes. Results were divided in two categories, speech-gesture match and speech-gesture mismatch. A majority of the student's gestures were simultaneous with speech and matched information (i.e., speech-gesture match). The other situations, when speech-gestures were a mismatch, included: students supplemented speech with gestures or in some cases the gestures were used to replace incorrect speech. Interestingly, the educator's use of gesture while providing descriptions influenced the student's gestures; students tended to mimic the educator's gestures when referencing a particular shape.

In a final study about communication gestures, de Freitas and Zolkower (2015) conducted a three-year study observing inner city eighth-grade students and their educators. Students gestured to convey the chunk of movement or duration (i.e., pinching gesture) to mark the continuity of unfolding event while they solved word problems associated with the direction of the graph. de Freitas and Zolkower (2015) learned gestures helped organize thought when paired with language because students created the object in the air using their hands and then transfer it to paper (de Freitas & Zolkower, 2015).

Why students gesture. Across the studies, students used gestures to organize (de Freitas & Zolkower, 2015) and communicate their mathematical understanding (Rosborough, 2014; Shein, 2012), even in cases when students were unable to do so verbally (Domínguez, 2005; Mainela-Arnold et al., 2011; Rosborough, 2014; Shein, 2012). One hypothesis as to why students gesture while learning mathematics, may be to reinforce their understanding and increase engagement during learning (Botzer & Yerushalmy, 2008; Francaviglia and Servidio, 2011; Reynolds & Reeves, 2001). For example, Francaviglia and Servidio (2011) observed five fifth-grade students while the students solved mathematics problems. Student gestures were coded as deictic, iconic, regulators, adaptors, or problem solving (descriptions outlined in Table 3). Students gestured approximately three times per min and generally matched their speech in communicating ideas during problem solving. Thus, students may use gestures to reinforce their verbal understanding of mathematical concepts. The researchers also concluded the gesture use by the student played an active role in attention and learning in mathematics problem solving. That is, gestures may play a role in increasing students' engagement during mathematical learning which in turn, increases students' understanding of the mathematical concepts.

Variation in students' use of gestures. Students gestured more when they learned new or challenging mathematics material (Graham, 1999; Kim et al., 2011; Logan et al., 2014). For example, Kim et al. (2011) observed use of gestures in 23 second-grade students during the geometry unit. Over 4 weeks, 15 sessions were recorded, each lasting 60 min. Gestures were coded by how the gesture related to speech, and these categories are outlined in Table 3. Student gesture use increased as a function of difficulty level. Specifically, as geometrical concepts became more complex, student gestures became more intricate and abstract in expressing the mathematical concepts. Similar results were seen learned of similar results with fourth- through sixth-grade students solving map-based mathematics problems (Logan et al., 2014). Gestures were defined as touching the page, counting on fingers, or drawing on the page. The researchers determined that students gestured more when solving a novel task or a task that was spatially challenging.

A similar pattern was found when students learned how to count. Graham (1999) observed gestures used during an object counting task in pre-kindergarten students. Researchers grouped students by age (i.e., 2-, 3-, or 4-years-old). More speech and gesture mismatches also occurred on more difficult trials (i.e., counting sets with greater number of objects) when compared to easier trials across all age groups. In addition, younger students tended to produce more speech and gesture mismatches than older students. The researchers concluded that students pointing to the objects while counting played an integral role in the development of early number knowledge in preschool students. That is, gesture mismatches with speech transitions to reinforcing students' verbal response as the student is able to count accurately. Across studies, during mathematics instruction, gestures acted as an active learning tool, or strategy to increase students' engagement, when new or difficult mathematical content was encounter (Graham, 1999; Kim et al., 2011; Logan et al., 2014).

Impact of the Use of Gestures by Students

As with educators, students' use of gestures impacted their performance on mathematics tasks (Alibali & DiRusso, 1999; Alibali & Goldin-Meadow, 1993; Broaders et al., 2007; Cook & Goldin-Meadow, 2006; Cook et al., 2008; Goldin-Meadow, Cook, & Mitchell, 2009; Novack, Congdon, Hemani-Lopez and Goldin-Meadow, 2014; Nicoladis et al., 2010). In addition, gestures also influenced students' performance on memory tasks (Goldin-Meadow et al., 2001), and helped shape their learning environment by influencing educators' instruction (Goldin-Meadow & Singer, 2003).

Across most of the studies, students performed higher on mathematics tasks when students use gestured, compared to when students did not gesture. For example, Alibali and DiRusso (1999) assigned students to five different conditions, (1) student pointing to objects (but not touch) while counting; (2) student touching objects while counting; (3) no gestures while counting; (4) student counts while a puppet pointing to objects; or (5) student counts while puppet touches objects. Students counted more accurately when students gestured themselves compared to the other conditions. Novack, Congdon, Hemani-Lopez and Goldin-Meadow (2014) determined similar positive effects for gestures while receiving instruction on mathematical equivalence problems. The researchers assigned third graders into an action condition, concrete gestures condition, or abstract gestures condition while receiving instruction. The uses of gestures by the students was shown to help students learn how to solve the mathematics problems. Specifically, students in concrete and abstract gesture group performed better on transfer equivalence problems than students in the action group. Thus, gesture use by students increased mathematical performance (Alibali & DiRusso, 1999; Novack et al., 2014).

Gestures also helped students transitions from learning to understanding mathematical concepts when students integrated gestures into their explanations. For example, Broaders and colleagues (2007) study 1, assigned third- and fourth-grade students to gestures, no gestures, or control conditions. Then, researchers asked students to explain how they solved mathematical equivalence problems. The number of the strategies used by students did not differ across groups when solving equivalence problems. However, most of the strategies produced uniquely in gestures, correctly portrayed mathematical explanations. In study 2, third- and fourth-grade students were assigned to gesture or no gesture conditions and asked to explain how they solved mathematical equivalence problems. A posttest of similar, but not exact mathematical equivalence problems, was administered to students. Students told to gesture solved significantly more problems correctly on the posttest than students told not to gesture. In addition, students that gestured when explaining mathematics problems expressed correct concepts that were not in their verbal explanation.

In a separate study, Cook and Goldin-Meadow (2006) assigned third and fourth graders to speech alone, no copy; speech alone, copy speech; speech and gesture, copy speech; and speech and gesture, copy gesture (see Table 3 for descriptions of conditions).

Students in the gesture condition produced gesture in their explanations of mathematical equivalence problems. The gestures used by the students reflected the content of the educators' gestures during mathematics instruction. Students that gestured in their explanation of mathematical equivalence problems were more likely to do better on posttest than students that did not use gestures in their explanation. These studies indicated that the effective gestures use could be taught to and be utilized by students to increase mathematics learning (Cook & Goldin-Meadow, 2006; Goldin-Meadow et al., 2009).

Alibali and Goldin-Meadow (1993) classified 90 fourth graders as gesturers or non-gesturers based on their natural use of gestures, during a training period solving mathematical equivalence problems. Students who gestured performed better on the posttest than students that did not gesture. In addition, the use of gestures in mathematical learning provided a successful mechanism to transition from not solving a mathematics equivalence problem successfully to solving it correctly. Mathematic retention was also associated with student use of gestures during mathematic instruction. For example, Cook et al. (2008) third and fourth graders were assigned into three groups: gesture, speech, or gesture and speech. Each group solved a comparable number of problems correctly during instruction and on the immediate posttest. Students that used gestures during instruction, however, were associated with significantly higher retention of mathematics material than the speech-only group.

Gestures were also shown to be a learning strategy that links new vocabulary with mathematical knowledge for students. For example, Goldin-Meadow et al. (2009) assigned third and fourth graders to mathematical equivalence instruction using gestures correctly, partially correct, or no gestures. Students then practiced problems using the type of instructions they were taught before completing a posttest. Students that correctly gestured during the lesson were more likely to correctly explain problems after the lesson and also performed higher on the posttest. Researchers concluded that gesturing enhanced student posttest performance by introducing the grouping strategy into their vocabulary.

Although gestures positively impact students' mathematics performance across most studies (Alibali & DiRusso, 1999; Alibali & Goldin-Meadow, 1993; Cook & Goldin-Meadow, 2006; Goldin-Meadow et al., 2009; Novack et al., 2014;), this was not the case, in one study (Nicoladis et al., 2010). Nicoladis and colleagues (2010) defined gestures as using fingers to match digits when they examined gestures in preschool students completing object counting and object-matching tasks. Students counted more accurately when mapping number words than number gestures onto objects. That is, students made less counting errors when they expressed the number of objects with the spoken number word (e.g., "two") than when using fingers to represent the number of objects (e.g., holding up 2 fingers to correspond to 2 objects). The researchers suggested that the use of number gestures do not help students map symbols to numbers words.

In addition to having an impact on students' mathematical performances, gestures also impacted students' memory. For example, Goldin-Meadow et al. (2001) examined students while they solved mathematical equivalence problems. Of the 40 students, researchers selected 26 (*M* age = 9 years, 11 months) to participate in the study based on their use of gesturing during solving the mathematics problems. These students performed a memory task, in which he or she had to recall words from a list that was read aloud to the students. Students explained how to solve the mathematical equivalence problems during the delay portion of the memory tasks. Students performed the task using gestures freely and also while being restricted from using gestures. Students remembered significantly more items when allowed to gesture than when not allowed to gesture. Further, gesturing benefited memory independently of mathematics performance.

Finally, in addition to being an effective strategy during mathematical learning, gestures can also influence instruction itself. For example, Gerosky's (2008) study 1 and 2 compared the use of gesture during calculus graph explanations between novice and experienced students. Gerosky coded gestures for placement of the *x*-axis against the gesturer's body, acceleration or deceleration in the gestural movement describing the graph, the presence or absence of eye tracking, engagement of the spine in movement, distal or proximal nature of the gesture, and parts of the body used to create the gesture. Results were consistent across both studies. The educator determines the student's understanding of material (i.e., above average, average, at-risk), based on their use of gestures during their calculus graph explanations. For example, average students tended to gesture higher against the body so that the graph would remain "within sight" (i.e., eye level tracking movement) compared to top students who gestured lower across the body to remain "within reach" (i.e., arms reach across body, straight out from the body, without spine movement; Gerosky, 2010). Students also reported that the use of gestures helped with recall information during the task. In another study, Goldin-Meadow and Singer (2003) measured gestures in third- and fourth-grade students (n = 34) during mathematics instruction. Educator uses of gestures during mathematics instruction and student performance on mathematical equivalence posttest were also collected. Educator instruction varied based on the type of gestures students used. Specifically, when a student provided gestures that mismatched speech, educators did the same during mathematics instruction. The researchers concluded that students could shape their learning environments in mathematics, by their use of gestures. Further, students that used gestures and speech that mismatched performed higher on the mathematical equivalence posttest than students that use gestures and speech that matched strategies. The researchers noted that the students that used gestures and speech that mismatched illustrated more than one correct strategy, while the students that use gestures and speech that matched strategies only portrayed one strategy.

In sum, when students gestured their performance across mathematics tasks increased (Alibali & DiRusso, 1999; Alibali & Goldin-Meadow, 1993; Cook & Goldin-Meadow, 2006; Goldin-Meadow et al., 2009; Novack et al., 2014). Use of gestures, however, did not improve counting accuracy in preschool students (Nicoladis et al., 2010). Gestures also helped students communicate their mathematical understanding (Broaders et al., 2007; Cook & Goldin-Meadow, 2006), even when they are unable to do so verbally (Mainela-Arnold et al., 2011). In addition, students use of gestures increased their performance on memory tasks (Goldin-Meadow et al., 2001) and influenced educators' instruction to have an impact on their learning environment (Goldin-Meadow & Singer, 2003). Again, it should be noted all of the studies examined the impact of gestures on preschool and elementary students. Also, the studies only included counting and mathematical equivalence problems. Thus, it is unclear if the effects of gestures seen across these studies can be generalized across other grade levels and mathematical content.

Discussion

The aim of this synthesis was to investigate how educators and students gestured during mathematics instruction. Further, the impact of gestures during mathematic instruction on students' performance was also examined. The findings across studies are summarized and the implications of the findings are discussed.

Educator Gestures

Educators gesture to express mathematical content to students. Many educators inherently gesture during mathematical instruction across elementary and middle school (Alibali et al., 2014; Flevares & Perry, 2001; Goldin-Meadow et al., 1999). The use of mathematical gestures generally corresponded to and reinforced educators' verbal instruction (Flevares & Perry, 2001; Goldin-Meadow et al., 1999), and educators tended to use gestures more than other non-verbal teaching representations (e.g., pictures, manipulatives) to instruct students in mathematics (Flevares & Perry, 2001). In addition, educators intuitively gestured more with new mathematical material (Alibali et al., 2014) or with mathematical content that students found confusing or difficult (Flevares & Perry, 2001).

When educators integrated gestures into mathematics instruction, it generally had positive results on students' mathematics performance (Alibali et al., 2013; Cook et al., 2013; Goldin-Meadow et al., 1999; Singer & Goldin-Meadow, 2005); however, some gestures are more effective than others. Specifically, elementary students' performance on mathematical equivalence problems increased when gestures provided additional information to verbal instruction (Singer & Goldin-Meadow, 2005). Fortunately, Alibali and colleagues (2013) found that educators could be trained to efficiently use gestures during mathematics instruction. Thus, instructing educators to use gestures with mathematical content is feasible and, in turn, could enhance student performance in mathematics.

Student Gestures

Across multiple studies, gesture use was as active learning strategy employed by students during mathematics instruction (Arzarello et al., 2009; Arzarello, Robutti, & Thomas, 2015; Bjuland et al., 2008; Botzer & Yerushalmy, 2008; de Freitas & Zolkower, 2015; Domínguez, 2005; Elia et al., 2014; Francaviglia & Servidio, 2011; Graham, 1999; Kim et al., 2011; Logan et al., 2014; Radford, 2009; Reynolds & Reeve, 2001; Warren et al., 2013; Zurina & Williams, 2011). That is, students gestured to illustrate reasoning strategies, create and connect mathematical representations, organize thoughts, and indicate and maintain attention during mathematical problem solving. For students who were learning a new language (i.e., English Learners), gestures bridged the two languages and provided a tool to depict mathematical understanding (Domínguez, 2005; Shein, 2012).

The use of gestures has been documented as early as preschool, when students develop early number knowledge by gesturing (i.e., pointing to the objects) while counting aloud (Graham, 1999). Students continue to use gestures as a mathematical learning approach, with gesture frequency increasing as a function of complexity. That is, students tend to gesture more when solving novel or challenging mathematical problems (Kim et al., 2011; Logan et al., 2014). Gestures were also used by students to transition from mathematical learning to comprehension and as method to refine conceptual understanding of mathematical content (Radford, 2009; Warren et al., 2013). Moreover, as students progress in their mathematics learning, students gestured more effectively by appropriately matching gestures to speech (Elia et al., 2014; Graham, 1999). Thus, research supports that student gesture plays an active role in attention and learning of mathematical content (Arzarello et al., 2009; Arzarello et al., 2015; Bjuland et al., 2008; de Freitas & Zolkower, 2015; Elia et al., 2014; Francaviglia & Servidio, 2011; Graham, 1999; Kim et al., 2011; Logan et al., 2014; Radford, 2009; Reynolds & Reeve, 2001; Warren et al., 2013; Zurina & Williams, 2011).

It is important to note that in one study, students counted more accurately when mapping number words onto objects, rather than number gestures (Nicoladis et al., 2010). This suggests that the use of gestures may not help across all mathematical domains (e.g., number gestures do not help students map symbols to numbers words) or grade levels. Because most of the studies examining gesture use in mathematics focus on mathematical equivalence, more research is needed to further examine the impact of gestures across different mathematical domains.

In addition to helping student mathematical learning, student use of gestures also influenced educator evaluation of student mathematical knowledge and impacted teaching decisions based on educator perceptions (Gerofsky, 2010; Goldin-Meadow & Singer, 2003). Student engagement during learning and student understanding of mathematical content was assessed by educators observing student gesture use, especially in students that were unable to verbally express their knowledge (Shein, 2012). That is, students that were observed having difficulty with gesturing during mathematical explanation were identified as at-risk by educators (Gerofsky, 2010). In addition, educator mathematics instruction varied based on the perception of mathematical comprehension established on student gesture use (Goldin-Meadow & Singer, 2003). Specifically, when a student provided gestures that mismatched speech, educators altered mathematics instruction to assist student with learning. In sum, students molded mathematical learning environments by successfully (or ineffectively) using gestures during mathematical instruction.

Student Performance

Effective gesture use during mathematical learning had a positive impact on student mathematical performance (Alibali et al., 2013). Educators effectively utilized gestures during mathematics instruction when verbal instruction was enhanced with a matching gesture (Goldin-Meadow et al., 1999). Student mathematics performance was also enriched when educators gestured to depict supplemental content (e.g., different strategy) to verbal mathematical instruction (Singer & Goldin-Meadow, 2005). When educator gestures were not accompanied by speech, however, students translated gestures into appropriate verbal explanations of mathematical content (Goldin-Meadow et al., 1999).

Researchers also determined that students retained more mathematical content and transferred mathematical knowledge to novel problems when gestures were used during mathematical instruction (Alibali & Goldin-Meadow, 1993; Cook et al., 2008; Cook et al., 2013; Novack et al., 2014). Similar to gesture use of educators, mathematical performance of students was enhanced when students used gestures effectively. That is, students that used gestures and verbal explanations that mismatched in mathematical strategies performed higher than students that use gestures that matched speech (Goldin-Meadow & Singer, 2003). Furthermore, the use of gestures helped students to express correct mathematical concepts that they could not do with verbal explanations alone (Broaders et al., 2007; Mainela-Arnold et al., 2011; Shein, 2012). In addition to enhancing mathematical performance, the use of gesture benefited student working memory (Goldin-Meadow et al., 2001). This may indicate that the use of gestures lightens the cognitive load of students, and thus increases mathematical performance.

Students that correctly imitated educator gestures during mathematical lessons were better at verbal explanations of mathematics content and performed higher on the posttest than students that did not gesture (Cook & Goldin-Meadow, 2006; Goldin-Meadow et al., 2009). Thus, teaching students to gesture during mathematics instruction was and is likely able to increase mathematical learning (Cook & Goldin-Meadow, 2006; Goldin-Meadow et al., 2009).

Research indicated that students with language impairments were also able to depict mathematical knowledge in gesture, even when mathematical understanding could not be expressed in speech (Mainela-Arnold et al., 2011). Specifically, students identified with expressive SLI exhibited correct strategies for mathematical equivalence problems using gestures but often articulated the incorrect strategies in verbal explanations. Analogously, gestures serve as a mediator for ELs to display mathematical knowledge when they were unable to depict understanding using speech (Rosborough, 2014; Shein, 2012). More research is needed to determine if gesture use is an appropriate approach to assess and instruct mathematical content for ELs and students with disabilities.

Limitations

There were several limitations of this research synthesis. First, this synthesis only included peer-reviewed journal articles, cultivating the file-drawer problem. That is, significant findings are more likely to be published than null effects, which may cause the significant findings of gestures in this synthesis to be oversampled. Due to possibility of positive bias of the significant effects of the use of gestures in math, caution should be used when interpreting these findings.

Another potential limitation is that over one-third (i.e., 14 of the 35) of the research examining use of gestures in mathematical content came from research teams led by

Martha Alibali and Susan Goldin-Meadow. Therefore, the samples used by these research groups may have been pulled from similar pools or the same population pool across studies. In addition, research questions and interpretations may potentially be at risk of bias due to large proportion of research contributed from the two research teams. Caution should be used when generalizing and interpreting the findings in the synthesis; however, the synthesis also includes 21 research items from other research teams. Furthermore, similar research findings and themes were found across research items providing support for meaningful and reliable conclusions.

Another limitation is the strong focus on gestures for use when explaining mathematical equivalence. In many ways, this relates to the second limitation of much of the literature originating from the same two research teams. That is, research groups tend to focus work on a single mathematical domain, which may have limited the mathematical content included in the synthesis. Again, caution should be used when interpreting and generalizing the findings beyond the mathematical domains that were examined in the synthesis. Further research needs to explore if the use of gestures during mathematical instruction is suitable across mathematical domains not included or minimally represented in the synthesis.

Implication of Findings and Future Directions

Despite these limitations, the findings in this synthesis has practical and theoretical implications for mathematic instruction. First, the literature supports that the integration of gestures into mathematics instruction can positively impact students' mathematical outcomes. Only one study, however, examined how different types of gestures can impact students' mathematics performance (Singer & Goldin-Meadow, 2005). Importantly, this study found that that gestures positively impacted third and fourth grade students' performance on mathematical equivalence problems when additional information was provided to verbal instruction. Future research should examine if these findings can be generalized to other grade levels and mathematical content. In addition, much research is needed to examine what specific aspects and types of gestures impacts students' mathematical learning.

Second, in addition to enhancing mathematical performance, the use of gesture may impact student working memory (Goldin-Meadow et al., 2001). Specifically, the use of gestures may reduce the cognitive load of students, and thus impact mathematical performance. This finding has theoretical implications in the construction of effective mathematical instructional strategies for students. That is, the integration of gestures into mathematical instruction could enhance learning for students. However, due to limited number of studies that explored the relationship between mathematics, working memory, and gestures additional research is needed.

Finally, the impact of gestures on working memory may also have practical implications for students with learning disabilities. Students identified with mathematical difficulties struggle to learn mathematic which may be, in part, due to deficits in working memory (Raghubar, Barnes, & Hecht, 2010). Thus, the findings from this synthesis indicate promise for the use of gestures for students identified with learning difficulties who may benefit from the reduction of cognitive processing in mathematical instruction. The majority of the research that examined gestures in mathematic was conducted with typically developing students. Therefore, further research is needed to examine the potential benefit of gestures in students with learning disabilities or students at-risk of a learning disability.

Conclusion

This synthesis aimed to summarize how educators use gestures during mathematics instruction and examine the impact of gestures on students' mathematics learning when educators use gestures during mathematics instruction. In addition, this synthesis also examined how students used gestures during mathematics learning and how gestures could be used to increase students' mathematics learning.

The use of gestures during mathematics instruction has a positive impact on student mathematical performance and memory, when gestures enhanced verbal instruction. Student mathematical performance was increased when educators gestured to accompany mathematic instruction and when students used gestures during mathematical learning. The use of gestures in mathematical learning is also practical and straightforward to instruct students and educators to use effectively. As educators are expected to adequately prepare all students to reason and communicate in mathematics, it is necessary that educators understand that one tool – gesture – may increase student knowledge about a variety of mathematical concepts and procedures and boost educator effectiveness.

References

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

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

*Alibali, M. W., Nathan, M. J., Wolfgram, M. S., Church, R. B., Jacobs, S. A., Johnson Martinez, C., & Knuth, E. J. (2014). How teachers link ideas in mathematics instruction using speech and gesture: A corpus analysis. *Cognition and Instruction, 32*, 65–100. https://doi.org/10.1080/07370008.2013.858161

*Alibali, M. W., Young, A. G., Crooks, N. M., Yeo, A., Wolfgram, M. S., Ledesma, I. M., . . . Knuth, E. J. (2013). Students learn more when their teacher has learned to gesture effectively. *Gesture, 13*, 210–233. https://doi.org/10.1075/gest.13.2.05ali

*Arzarello, F., Paola, D., Robutti, O., & Sabena, C. (2009). Gestures as semiotic resources in the mathematics classroom. *Educational Studies in Mathematics, 70*, 97–109. https://doi.org/10.1007/s10649-008-9163-z

*Arzarello, F., Robutti, O., & Thomas, M. (2015). Growth point and gestures: looking inside mathematical meanings. *Educational Studies in Mathematics, 90*, 19–37. https://doi.org/10.1007/s10649-015-9611-5

*Bjuland, R., Luiza Cestari, M., & Borgersen, H. E. (2008). The interplay between gesture and discourse as mediating devices in collaborative mathematical reasoning: A multimodal approach. *Mathematical Thinking and Learning, 10*, 271–292.

https://doi.org/10.1080/10986060802216169

*Botzer, G., & Yerushalmy, M. (2008). Embodied semiotic activities and their role in the construction of mathematical meaning of motion graphs. *International Journal of Computers for Mathematical Learning*, 13, 111–134. https://doi.org/10.1007/s10758-008-9133-7

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

Bruner, J. S. (1966). *Toward a theory of instruction*. Cambridge, MA: Harvard University Press.

Cameron, H., & Xu, X. (2011). Representational gesture, pointing gesture, and memory recall of preschool children. *Journal of Nonverbal Behavior, 35*, 155–171. https://doi.org/10.1007/s10919-010-0101-2

Child, S., Theakston, A., & Pika, S. (2014). How do modelled gestures influence preschool children's spontaneous gesture production? Social versus semantic influence. *Gesture, 14*, 1–25. https://doi.org/10.1075/gest.14.1.01chi

Cochet, H., Centelles, L., Jover, M., Plachta, S., & Vauclair, J. (2015). Hand preferences in preschool children: reaching, pointing, and symbolic gestures. *Laterality, 20,* 501–516. https://doi.org/10.1080/1357650X.2015.1007057

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

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

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

*Cook, S. W., & Goldin-Meadow, S. (2006). The role of gesture in learning: Do children use their hands to change their minds? *Journal of Cognition and Development, 7*, 211–232. https://doi.org/10.1207/s15327647jcd0702_4

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

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

*de Freitas, E., & Zolkower, B. (2015). Tense and aspect in word problems about motion: diagram, gesture, and the felt experience of time. *Mathematics Education Research Journal, 27*, 311–330. https://doi.org/10.1007/s13394-014-0139-2

de Nooijer, J. A., van Gog, T., Paas, F., & Zwaan, R. A. (2014). Words in action: Using gestures to improve verb learning in primary school children. *Gesture, 14*, 46–69. https://doi.org/10.1075/gest.14.1.03noo

*Domínguez, H. (2005). Bilingual students' articulation and gesticulation of mathematical knowledge during problem solving. *Bilingual Research Journal, 29*, 269–293.

https://doi.org/10.1080/15235882.2005.10162836

Dougherty, C. (2003). Numeracy, literacy and earnings: evidence from the National Longitudinal Survey of Youth. *Economics of Education Review, 22*, 511–521. https://doi.org/10.1016/50272-7757(03)00040-2

Dunlosky, J., Rawson, K. A., Marsh, E. J., Nathan, M. J., & Willingham, D. T. (2013). Improving students' learning with effective learning techniques promising directions from cognitive and educational psychology. *Psychological Science in the Public Interest, 14*, 4–58. https://doi.org/10.1177/1529100612453266

*Elia, I., Gagatsis, A., & van den Heuvel-Panhuizen, M. (2014). The role of gestures in making connections between space and shape aspects and their verbal representations in the early years: Findings from a case study. *Mathematics Education Research Journal, 26*, 735–761. https://doi.org/10.1007/s13394-013-0104-5

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

*Francaviglia, M., & Servidio, R. (2011). Gesture as a cognitive support to solve mathematical problems. *Psychology, 2*, 91–97. https://doi.org/10.4236/psych.2011.2201

*Gerofsky, S. (2010). Mathematical learning and gesture: Character viewpoint and observer viewpoint in students' gestured graphs of functions. *Gesture, 10*, 321–343. https://doi.org/10.1075/gest.10.2-3.10ger

Goldin-Meadow, S. (2004). Gesture's role in the learning process. *Theory Into Practice, 43*, 314–321. https://doi.org/10.1207/s15430421tip4304_10

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

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

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

*Goldin-Meadow, S., & Singer, M. A. (2003). From children's hands to adults' ears: gesture's role in the learning process. *Developmental Psychology, 39*, 509–520. https://doi.org/10.1037/0012-1649.39.3.509

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

Kilpatrick, J., Swafford, J., & Findell, B. (2001). *Adding it up.* Washington, DC: National Academies Press.

*Kim, M., Roth, W., & Thom, J. (2011). Children's gestures and the embodied knowledge of geometry. *International Journal of Science and Mathematics Education, 9*, 207–238. https://doi.org/10.1007/s10763-010-9240-5

Lakoff, G., & Núñez, R. (2000). *Where mathematics comes from: The embodied mind brings mathematics into being*. New York, N.Y.: Basic Books.

*Logan, T., Lowrie, T., & Diezmann, C. M. (2014). Co-thought gestures: Supporting students to successfully navigate map tasks. *Educational Studies in Mathematics, 87*, 87–102. https://doi.org/10.1007/s10649-014-9546-2

*Mainela-Arnold, E., Alibali, M. W., Ryan, K., & Evans, J. L. (2011). Knowledge of mathematical equivalence in children with specific language impairment: Insights from gesture and speech. *Language, Speech, and Hearing Services in Schools, 42*, 18–30. https://doi.org/10.1044/0161-1461(2010/09-0070)

National Governors Association Center for Best Practices & Council of Chief State School Officers. (2010). *Common Core State Standards mathematics.* Washington, DC: Authors.

*Nicoladis, E., Pika, S., & Marentette, P. (2010). Are number gestures easier than number words for preschoolers? *Cognitive Development, 25*, 247–261. https://doi.org/10.1016/j.cogdev.2010.04.001

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

Novack, M., & Goldin-Meadow, S. (2015). Learning from gesture: How our hands change our minds. *Educational Psychology Review, 27*, 405–412. https:doi.org/10.1007/s10648-015-9325-3

Olson, J., & Masur, E. F. (2011). Mothers' labeling responses to infants' gestures predict vocabulary outcomes. *Journal of Child Language, 42*, 1289–1311. https://doi.org/10.1017/S0305000914000828

*Radford, L. (2009). Why do gestures matter? Sensuous cognition and the palpability of mathematical meanings. *Educational Studies in Mathematics, 70*, 111–126. https://doi.org/10.1007/s10649-008-9127-3

Raghubar, K.P., Barnes, M.A., & Hecht, S. (2010). Working memory and mathematics: A review of developmental, individual difference, and cognitive approaches. Learning and Individual Differences, 20, 110-122. doi: https://doi.org/10.1016/j.lindif.2009.10.005

*Reynolds, F. J., & Reeve, R. A. (2001). Gesture in collaborative mathematics problem-solving. *The Journal of Mathematical Behavior, 20*, 447–460. https://doi.org/10.1016/S0732-3123(02)00091-3

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

Rittle-Johnson, B., Fyfe, E. R., Hofer, K. G., & Farran, D. C. (2017). Early math trajectories: Low-income children's mathematics knowledge from ages 4 to 11. *Child Development, 88*, 1727–1742. https://doi.org/10.1111/cdev.12662

*Rosborough, A. A. (2014). Gesture, meaning-making, and embodiment: Second language learning in an elementary classroom. *Journal of Pedagogy, 5*, 227–250. https://doi.org/10.2478/jped-2014-0011

Rubenstein, R. N., & Thompson, D. R. (2002). Understanding and supporting children's mathematical vocabulary development. *Teaching Children Mathematics, 9*, 107–112.

Schleppegrell, M. J. (2012). Academic language in teaching and learning introduction to the special issue. *The Elementary School Journal, 112,* 409–418.

https://doi.org/10/1086/663297

Sekine, K. (2011). The role of gesture in the language production of preschool children. *Gesture, 11*, 148–173. https://doi.org/10.1075/gest.11.2.03sek

*Shein, P. P. (2012). Seeing with two eyes: A teacher's use of gestures in questioning and revoicing to engage English language learners in the repair of mathematical errors. *Journal for Research in Mathematics Education, 43*, 182–222. https://doi.org/10.5951/jresematheduc.43.2.0182

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

*Warren, E., Miller, J., & Cooper, T. J. (2013). Exploring young students' functional thinking. *PNA, 7*, 75–84.

Wilson, J. (2012). Show Me a Sign. *Teaching Children Mathematics, 19*, 82-89. doi:10.5951/teacchilmath.19.2.0082

Zampini, L., Zanchi, P., Suttora, C., Spinelli, M., Fasolo, M., & Salerni, N. (2016). Gesture production in the narratives of preschool children. *Gesture, 15*, 306–320. https://doi.org/10.1075/gest.15.3.02zam

*Zurina, H., & Williams, J. M. (2011). Gesturing for oneself. *Educational Studies in Mathematics, 77*, 175–188. https://doi.org/:10.1007/s10649-010-9294-x

Table 1
Summary of Articles (N = 35)

Characteristic	*n*	%
Publication year		
1990–1990	4	11.4%
2000–2009	14	40.0%
2010–present	17	48.6%
Grade level[a]		
Preschool	4	11.4%
Elementary (K–5)	21	60.0%
Middle (6–8)	7	20.0%
High (9–12)	7	20.0%
Observed gesturer[a]		
Student	33	94.3%
Teacher	9	25.7%
Student type[a]		
Typically developing or NR	30	85.7%
English Learners	4	11.4%
At-risk or with disability	1	2.9%
Only teachers	2	5.7%
Mathematical content		
Counting	4	11.4%
Equivalence	12	34.3%
Geometry	4	11.4%
Graphing	7	20.0%
Other	8	22.9%
Total sample size		
<5	7	20.0%
5 to 25	10	28.6%
25 to 50	7	20.0%
>50	10	28.6%
NR	1	2.9%
Study type		
Qualitative		
Descriptive narrative	14	40.0%
Quantitative		
Frequency counts	9	25.7%
Correlational	2	5.7%
Experimental	10	28.6%
Total quantitative	21	60.0%

Note. K = Kindergarten; NR = Not reported
[a]Several studies included more than one category.

Table 2
Qualitative Data

Study	Grade	Total minutes and number of sessions	Participant observed	*n*	Math content	Gesture code or results	Use of gestures
Arzarello et. al. (2009)	11	NR min NR session	Students & educator	NR (students & educators)	Calculus graphing	(1) Institutional (2) Personal	Learning
Arzarello et al. (2015) Study 1	preK[a]	NR min 1 session	Student	1	Counting 3 objects	(1) Iconic (2) Deictic (3) Metaphoric	Learning
Arzarello et al. (2015) Study 2	11	NR min 1 session	Student	1	Calculus graphs	(1) Iconic (2) Deictic (3) Metaphoric	Learning
Bjuland et al. (2008)	6	19 min 1 session	Students	5	Cartesian graphs	(1) Repeated pointing (2) Consecutive pointing (3) Held-point (4) Point-slide (5) Linear point- slide (6) Circular point slide	Learning
Botzer & Yerushalmy (2008)	11-12[a]	240 min 4 sessions	Students	2	Calculus graphing	(1) Static representations (2) Attention (3) 2D motion: parametric graph presentations (4) Semiotic mediation	Communication
de Freitas & Zolkower (2015)	8	NR min 3 sessions	EL/EP Students & educators	84 (students) 3 (educators)	Word problems about time and motion	Descriptive narrative	Communication
Domínguez (2005)	2	NR min 3 sessions	EL students	7	Addition and subtraction computation	(1) Repeat or add to verbal behavior (2) Substitution (3) Simultaneous	Communication
Elia et al. (2014)	K	NR min NR session	Student & educator	1 (student) 1 (educator)	Geometric shapes	(1) Iconic (2) Deictic (3) Metaphoric	Communication

Table 2 continued

Study	Grade	Total minutes and number of sessions	Participant observed	*n*	Math content	Gesture code or results	Use of gestures
Gerofsky (2010) Study 1	8 and 11	NR min 2 sessions	Students	11 (8th graders) 11 (11th graders)	Calculus graph explanations	(1) Placement of the *x*-axis against the gesturer's body (2) Acceleration/ deceleration in the gestural movement describing the graph (3) The presence or absence of eye tracking (4) Engagement of the spine in movement (5) Distal or proximal nature of the gesture (6) Parts of the body used to create the gesture	Learning
Gerofsky (2010) Study 2	8 and 12	60 min 6 sessions (8-month span)	Students	25	Graphs of polynomial functions	(see Gerofsky [2010] Study 1)	Learning
Radford (2009)	10	NR min 1 session	Students	3	Time-distance graphs	(1) Semiotic nodes (2) Configuration (3) Objectification	Learning
Reynolds & Reeve (2002)	8 & 9	30 min 2 sessions	Students	1 (8th grader) 1 (9th grader)	Graphs	Description of how gestures are used with speech	Communication
Rosborough (2014)	2	NR min 1 session	EL student	1	Numeracy	(1) Beat (2) Iconics (3) Deictics (4) Metaphors (5) Emblems	Communication
Shein (2012)	5	NR min 9 sessions	EL students & educator	6 (students) 1 (educator)	Area of geometry shapes	(1) Pointing (2) Representational (3) Writing	Communication
Warren et al. (2013)	K[a]	20 min 1 session	Students & researchers	6 (students) 2 (researchers)	Geometry shapes and numeracy	Description of how gestures are used with speech	Learning
Zurina & Williams (2011)	7[a]	NR min NR session	Students	36	Fractions	(1) Gesticulation (2) Objectification (3) Visualization	Learning

[a]Determined based on age of students as reported by authors.

Table 3
Quantitative Data

Study	Grade	Observed	*n*	Study Type	Math content	Student outcome	Gesture variable	Gesture coding/ Gesture related group assignment	Results
Alibali & DiRusso (1999)	pre-K	Student	20	Experimental	Object counting	Counting	IV	Students counted objects in each phase: (1) no instructions on pointing or touching (2) point to objects (but not touch) while counting (3) touch objects while counting (4) use no gestures while counting (5) puppet pointing to objects as student counted (6) puppet touched objects as student counted (7) puppet made errors as student counted	With both small and large number sets, students counted more accurately when they touched objects than when they pointed to objects. Student performance was slightly better when they gestured themselves than when the puppet gestured.
Alibali & Goldin-Meadow (1993)	4	Student	63 (gesturers) 27 (non-gesturers)	Correlational	Math equivalence	Math equivalence	IV	Gestures either matched or mismatched speech Students identified as: (1) Gesturers: Students that gestured during training period (2) Non-gesturers: Students that did not gesture at all or on fewer than 2 problems	Students who gestured performed better at posttest than students that did not gesture. The use of gestures also helped students transition from solving a problem incorrectly to solving it correctly.
Alibali et al. (2013)	7	Educator, Student	1 (educator) 42 (students; number of students in each group not reported)	Experimental	Linear equations (slope, intercept)	Graphs and equations	DV; IV	Gestures coded as: (1) Points: involve extending a finger (usually the index finger) or the entire hand (2) Depictive: depict meaning either via handshape or motion trajectory (3) Tracing: trace a path along an object (4) Writing: aligned with speech (5) Beats: rhythmic, up-and-down hand movements often aligned with the prosody of speech and that have no clear semantic meaning (6) Linking episodes: segments of discourse in which the educator sought to link two (or in some cases, three or more) math ideas Students assigned to watch instruction: (1) Enhanced-gesture: student received instruction after educator had received gesture training on how to use gestures to link concepts in math (2) Control: student received instruction prior to educator receiving gesture training	After the training, the educator increased the frequency of gesture use to link ideas in math instruction. There was group difference for understanding of graphs and equations at posttest. Specifically, students had greater gains in the enhanced gesture condition than control condition for understanding of intercept.

Table 3 continued

Study	Grade	Observed	*n*	Study Type	Math content	Student outcome	Gesture variable	Gesture coding/ Gesture related group assignment	Results
Alibali et al. (2014)	6-8	Educator	6	Descriptive with frequency counts	Mixed	–	DV	Gestures coded as: (1) Linking episodes: *segments of discourse in which teachers sought to link ideas* (2) Sequentially: *first gestured to indicate or represent one idea, then gestured to indicate or represent another idea* (3) Simultaneously: *gestured to indicate or represent one idea with one hand and another idea with the other hand, at the same moment;* (4) Pointing: *indicate objects, locations, or inscriptions, usually with an extended finger or hand* (5) Depictive: *depict aspects of semantic content directly, via hand shape or motion trajectory, either literally or metaphorically* (6) Beat: *motorically simple rhythmic movements that do not carry semantic content but that often align with the prosody or discourse structure of speech* (7) Writing: *writing or drawing actions that were integrated with speech in the way that hand gestures are typically integrated with speech but that were produced while holding a writing*	All educators used sequential gestures more when they linked ideas in speech and gesture than simultaneous gestures. Educators gestured at a higher rate for links that involved new material than review material.
Broaders, Cook, Mitchell, & Goldin-Meadow (2007)	3-4	Student	Study 1: 33 (Gesture) 35 (No gesture) 38 (Control) Study 2: 36 (Gesture) 34 (No gesture)	Experimental	Math equivalence	Math equivalence	DV, IV	Correct gesture strategies: (1) Equalizer: *Flat palm sweeps first under the left side of the problem and then under the right* (2) Equal-addends and grouping: *One flat palm covers the left side of the problem and another covers the right; V-hand indicates the left side of the problem* (3) Add–subtract: *Pointing hand sweeps under the left side of the problem; hand points to the right side and retracts; hand points to the blank* Incorrect strategies (1) Add all numbers: Point to all numbers and the blank (2) Add to equal sign: Point at the numbers on the left side and the blank (3) Carry: Point at the number and the blank Students assigned to: (1) Gesture: Students asked to use hands during their explanation (2) No gesture: Students asked to keep their hands still during their explanations (3) Control: Students asked to provide explanations with no mention of the use of hands (Control condition only in Study 1)	Study 1: The number of gesture strategies used by students did not differ across groups. However, most of the strategies produced uniquely in gesture were correct. Study 2: Students told to gesture solved significantly more problems correctly at posttest than students told not to. Students that utilized gestures when explaining math problems expressed correct concepts that were not in their verbal explanation.

Table 3 continued

Study	Grade	Observed	*n*	Study Type	Math content	Student outcome	Gesture variable	Gesture coding/ Gesture related group assignment	Results
Cook, Duffy, & Fenn (2013)	2-4	Student	184 (*n* for each group not reported)	Experimental	Math equivalence	3 tests of addition math equivalence and 2 transfer tests	IV	Students assigned to: (1) Gesture videos, with the instructor using hand gestures while speaking, using different hands to refer to the two sides of the equation (2) Speech-alone, using exactly the same verbal scripts and intonation. However, in these videos, the instructor's hands rested naturally at her side, and no gestures were produced.	Students performed better at posttest and transfer test when in the speech and gesture condition than the speech-alone condition.
Cook & Goldin-Meadow (2006)	3-4	Student	10 (Speech alone, no copy) 10 (Speech alone, copy speech) 10 (Speech and gesture, no copy) 10 (Speech and gesture, copy speech) 9 (Speech and gesture, copy gesture)	Experimental	Math equivalence	Math equivalence	IV	Students assigned to: (1) Speech alone, no copy: Student provided verbal instruction and asked to explain their answers (2) Speech alone, copy speech: Student provided verbal instruction and asked to copy instructions for their answers (3) Speech and gesture, no copy: Student provided verbal instruction with gestures and asked to explain their answers (4) Speech and gesture, copy speech: Student provided verbal instruction with gestures and asked to copy verbal instructions for their answers (5) Speech and gesture, copy gesture: Student provided verbal instruction with gestures and asked to copy gesture instructions for their answers	Students in the gesture conditions produced gestures in their explanations. These gestures reflected the content of the educators' gestures. Students that used gestures in their explanation were more likely to do better on posttest.
Cook, Mitchell, & Goldin-Meadow (2008)	3-4	Student	30 (gesture) 25 (speech and gesture) 29 (speech only)	Experimental	Math equivalence	Math equivalence	IV	Students assigned to: (1) Gesture (2) Speech and gesture (3) Speech only condition	All groups solved comparable numbers of problems correctly during instruction and at immediate posttest. However, students that used gestures during instruction were associated with significantly more retention than the speech only group.
Flevares & Perry (2001)	1	Educator	3	Descriptive with frequency counts	Place value	–	DV	Gestures conveying math content: (1) Pointing to indicate another representation type (2) Symbolic gestures (e.g., finger counting or using hands to indicate grouping of counting items)	Educators conveyed information using math-related gestures more than the other three representation modalities (i.e., pictures, concrete objects, written symbols). Educators presented the majority of their content using more than one representation, and the combinations almost always included a math gesture.

Table 3 continued

Study	Grade	Observed	*n*	Study Type	Math content	Student outcome	Gesture variable	Gesture coding/ Gesture related group assignment	Results
Francaviglia & Servidio (2011)	5	Student	5	Descriptive with frequency counts	Problem solving	–	DV	Gestures coded as: (1) Deictic: used to move the listener attention from the speaker to object being discussed (2) Iconic: used to illustrate speech (3) Regulators: support communication between individuals; (4) Adaptors: used unintentional (5) Problem solving: used when working together to solve a math problem	Student gestures matched with their speech. Researchers concluded gestures play an active role of attention in the learning process.
Goldin-Meadow, Cook, & Mitchell (2009)	3-4	Student	43 (correct-gesture) 43 (partially correct gesture) 42 (no gesture)	Experimental	Math equivalence	Math equivalence (solve and explain each problem)	IV	Students assigned to: (1) Correct-gesture condition: Taught how to solve an equation using gestures to point with V-hand to one side and point with index finger to the other side (2) Partially correct gesture condition: Taught how to solve an equation using the same gestures except the V-hand pointed to numbers whose sum is not the correct answer (3) No gestures	Students that correctly gestured during lesson were more likely to explain problems correctly after the lesson and perform higher at posttest. Researchers concluded that gesturing enhances student posttest performance by introducing the grouping strategy into their vocabulary.
Goldin-Meadow, Kim, & Singer (1999)	3-4	Educator, Student	8 (educators) 49 (students)	Descriptive with frequency counts	Math equivalence	Math equivalence	DV	Correct gesture strategies: (1) Equalizer: *Flat palm sweeps first under the left side of the problem and then under the right* (2) Equal-addends and grouping: One flat palm covers the left side of the problem and another covers the right; V-hand indicates the left side of the problem (3) Add–subtract: Pointing hand sweeps under the left side of the problem; hand points to the right side and retracts; hand points to the blank Incorrect gesture strategies (1) Add all numbers: Point to all numbers and the blank (2) Add to equal sign: Point at the numbers on the left side and the blank; (3) Carry: Point at the number and the blank Building gesture strategies (1) Left side: *Flat palm held under left side of problem* (2) Right side: *Flat palm sweeps from left to right under the right side of the problem*	Educators expressed a large portion of problem-solving strategies nonverbally. Gestures were generally used to reinforce speech by conveying the same strategy. Students were able to translate educators' gestures not accompanied with speech into a verbal response. Students were also able to understand strategies better when speech was accompanied with gestures.

Table 3 continued

Study	Grade	Observed	*n*	Study Type	Math content	Student outcome	Gesture variable	Gesture coding/ Gesture related group assignment	Results
Goldin-Meadow, Nusbaum, Kelly, & Wagner (2001)	3-5 (NR)	Student	26	Experimental	Math equivalence	–	IV	Gestures were described in terms of hand shape, motion, and location in space.	Students remembered significantly more items when allowed to gesture than when not allowed to gesture. Further, gesturing benefited memory independently of math performance.
Goldin-Meadow & Singer (2003)	3-4	Educator, Student	8 (educators) 38 (students)	Descriptive with frequency counts	Math equivalence	Math equivalence	DV	Correct gesture strategies: (1) Equalizer: Flat palm sweeps first under the left side of the problem and then under the right (2) Equal-addends and grouping: One flat palm covers the left side of the problem and another covers the right; V-hand indicates the left side of the problem (3) Add–subtract: Pointing hand sweeps under the left side of the problem; hand points to the right side and retracts; hand points to the blank Incorrect gesture strategies (1) Add all numbers: Point to all numbers and the blank (2) Add to equal sign: Point at the numbers on the left side and the blank (3) Carry: Point at the number and the blank Building gesture strategies (1) Left side: Flat palm held under left side of problem (2) Right side: Flat palm sweeps from left to right under the right side of the problem Students identified as: (1) Mismatch in pre-test and instruction: During pre-test and instruction, students that use gesture and speech strategies that do not match (2) Mismatch in instruction: During instruction, students that use gesture and speech strategies that do not match (3) No Mismatch: During pre-test and instruction, students that use gesture and speech strategies that do match	Educator instruction varied based on the type of gestures students used. When students provided gestures that mismatched speech, educators did the same. Students that used gestures and speech that mismatched performed higher on the math equivalence posttest than students than students that use gestures and speech that matched strategies.
Graham (1999)	Pre-K	Student	29 (2 year olds) 25 (3 year olds) 31 (4 year olds)	Descriptive with frequency counts	Object counting	Object counting	DV	Gestures were categorized as use of finger(s) or hand pointing toward or touching the objects being counted. Sweeping of the finger(s) or hand was also noted.	Younger students tended to produce more speech and gesture mismatches then older students. More speech and gesture mismatches also occurred on more difficult trials when compared to easier trials.

Table 3 continued

Study	Grade	Observed	*n*	Study Type	Math content	Student outcome	Gesture variable	Gesture coding/ Gesture related group assignment	Results
Kim, Roth, & Thom, (2011)	2	Student	23	Descriptive with frequency counts	Geometry	–	DV	Only gestures related to learning were coded. Gestures were categorized as containing: (a) No speech and no communicative purpose (b) Speech and communicative purpose (c) Speech toward others (d) Speech not directed toward others	As the geometrical concepts became more complex, student gestures became more intricate and abstract in expressing the math concepts.
Logan, Lowrie, & Diezmann (2014)	4-6	Student	43	Descriptive with frequency counts	Map navigation	–	DV	Gestures were categorized as touching the page, counting on fingers, or drawing on the page.	Students gestured more when solving a novel task or spatial challenging tasks.
Mainela-Arnold, Alibali, Ryan, & Evans (2011)	3-5 (NR)	Student	9 (expressive SLI) 8 (expressive & receptive SLI) 17 (typical-developing children)	Correlation	Math equivalence	Math equivalence	–	Correct gesture strategies: (1) Grouping: *indicate the numbers that do not appear on both sides. May also indicate the number that appears on both sides, but in a way that is differentiated from the others (i.e., in a different gesture unit, marked by putting hand down or by using a different handshape)* (2) Add–subtract: i*ndicate all numbers on the left side, then indicate the number on the right side in a way that is differentiated from the others (i.e., in a different gesture unit, marked by putting hand down or by using a different handshape)* (3) Equalize: *indicate all numbers on the left side, then indicate all numbers on the right side in a way that is differentiated from the left side(i.e., in a different gesture unit, marked by putting hand down or using a different handshape)* Incorrect gesture strategies (1) Add all numbers: i*ndicate all numbers in the problem without differentiating the addend on the right side from the others* (2) Add to equal sign: *indicate all numbers on the left side* Gestures coded as: (1) Gesture-speech match (2) Gesture-speech mismatch (3) Speech alone	Students identified with expressive and receptive SLI exhibited more incorrect strategies for solving math equivalence problems in both their speech and gestures than the other groups. Students identified with expressive SLI exhibited correct strategies in gestures, however often the incorrect strategies in speech.
Nicoladis, Pika, & Marentette (2010)	pre-K	Student	11 (2 year olds) 11 (3 year olds) 11 (4 year olds) 11 (5 year olds)	Descriptive with frequency counts	Object counting and matching	Object counting	DV	Gestures were categorized as using fingers to match digits.	Students counted more accurately when mapping number words than number gestures onto objects. Researchers suggested the use of number gestures did not help students map symbols to number words.

Table 3 continued

Study	Grade	Observed	*n*	Study Type	Math content	Student outcome	Gesture variable	Gesture coding/ Gesture related group assignment	Results
Novack, Congdon, Hemani-Lopez, & Goldin-Meadow (2014)	3	Student	30 (action group) 31 (concrete group) 29 (abstract group)	Experimental	Math equivalence	Math equivalence	IV	Students assigned to: (1) Action: *"I want to make one side [while simultaneously picking up the first two number tiles, the 2 and 9 in this example] equal to the other side [while simultaneously placing the number tiles on the blank space]."* (2) Concrete: *"I want to make one side [while simultaneously moving their hands as if picking up the first two number tiles, but not physically touching the pieces] equal to the other side [while simultaneously pretending to place the number tiles on the blank space without physically moving the tiles]."* (3) Abstract: *"I want to make one side [while simultaneously producing a V-point gesture under the first two numbers] equal to the other side [while simultaneously pointing with their index finger to the blank space]."*	Gestures helped children learn how to solve the problems. Students in concrete and abstract gesture group performed better on transfer problems than students in the action group.
Singer & Goldin-Meadow (2005)	3-4	Student	160 in all with ~ 27 (in each condition)	Experimental	Math equivalence	Math equivalence	IV	Students assigned to: (1) Gestures either matched strategy in speech (2) Gestures different from the spoken strategy (3) No gestures	Students performed better when gestures were used but only when gestures conveyed a different strategy than speech.

Note. Italicized text is directly from citation; When grade not reported (NR) this value was estimated by authors using the age, based on US standards; SLI = Specific Language Impairment