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Give yourself a hand: The role of gesture and working memory in preschoolers' numerical knowledge

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Hand gestures can be beneficial in math contexts to reduce the user's cognitive load by supporting domain-general abilities such as working memory. Although prior work has shown a strong relation between young children's early math performance and their general cognitive abilities, it is important to consider how children's working memory ability may relate to their use of spontaneous gesture as well as their math-specific abilities. The current study examined how preschool-aged children's gesture use and working memory relate to their performance on an age-appropriate math task. Head Start preschoolers (N = 81) were videotaped while completing a modified version of the Give-N task to measure their cardinality understanding. Children also completed a forward word span task and a computerized Corsi Block task to assess their working memory. The results showed that children's spontaneous gesture use and working memory were related to their performance on the cardinality task. However, children's gestures were not significantly related to working memory after controlling for age. Findings suggest that young children from low-income backgrounds use gestures during math contexts in similar ways to preschoolers from higher-income backgrounds.

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Introduction

The factors that affect children's early mathematical learning are critical to understand because these early abilities are strongly linked to later math achievement (Claesens & Engel, 2013; Geary, Hoard, Nugent, & Bailey, 2013; Watts, Duncan, Siegler, & Davis-Kean, 2014). One such factor is working memory (WM), which is people's domain-general ability to hold information in their mind while simultaneously carrying out a mental process (Baddeley & Hitch, 1974). Prior work has shown a consistent link between children's domain-general WM abilities and their early math success (see Clements, Sarama, & Germeroth, 2016, for a recent review).

Another factor that affects children's math learning is their use of and exposure to nonverbal communication methods such as hand gestures. Gestures play a role in children's acquisition of novel math concepts (Broaders, Cook, Mitchell, & Goldin-Meadow, 2007). Specifically, gestures are thought to facilitate math learning through a reduction of cognitive demands (Cook, Yip, & Goldin-Meadow, 2012; Goldin-Meadow, Nusbaum, Kelly, & Wagner, 2001) and direction of attention (Wakefield, Novack, Congdon, Franconeri, & Goldin-Meadow, 2018). Thus, when children use gestures during math instruction, they can recruit specific cognitive resources that might not otherwise be readily available. However, less is known about the combined relation among children's gesture use, WM, and mathematics performance.

The current work examines how preschool-aged children's gesture use and WM relate to their performance on a cardinality task. Whereas prior work has focused on each of these relations independently (i.e., gesture and WM, WM and math, and gesture and math separately), we sought to explore potential interdependencies among them. In addition, we were interested in examining these skills with a sample of preschool-aged children given the concurrent and rapid development of both math-related knowledge and executive functions.

Gestures in mathematical contexts

Gestures are bodily movements involving the use of hands that appear spontaneously alongside and in complement to our speech (Kendon, 1994). Gestures are theorized to play a role in cognitive development because they are useful during communication for both the listener and the speaker (Goldin-Meadow & Beilock, 2010; Goldin-Meadow, Cook, & Mitchell, 2009). This has important implications when considering how and why a child may use gestures within a math environment. Critically, children's gestures can display implicit information that does not otherwise appear in speech. (Broaders & Goldin-Meadow, 2010; Goldin-Meadow, Wein, & Chang, 1992; Iverson & Goldin-Meadow, 2005; McNeill, 1992). Indeed, children who are instructed to gesture during difficult math tasks have shown evidence of new and correct problem-solving strategies in their gestures (Broaders et al., 2007). Thus, children's gestures have the capacity to both show and scaffold children's own math learning.

Prior research has focused on the role of gesture in mathematical contexts primarily for school-age children. These learning environments typically involve processing both visual and auditory information that can be aided by gestures (Goldin-Meadow, Kim, & Singer, 1999). Gestures may also be important during early childhood when children are learning foundational numerical concepts such as counting and cardinality. The cardinality principle is the rule that the last word in a correctly recited count list is representative of the number of items in the set (Gelman & Gallistel, 1978). During this process of learning to count, children first learn the meaning of the numerosity "one," followed by "two," and so on (Le Corre, Van de Walle, Brannon, & Carey, 2006; Sarnecka & Gelman, 2004). Children's understanding of numbers can be assessed through how and when children use the cardinality principle within the Give-a-Number task (Give-N; e.g., Wynn 1990, 1992). During this task, children are asked to create different set sizes of objects. The highest numeric set size that children are able to create reliably provides information regarding their current level of understanding for cardinality and counting principles.

Counting and cardinality tasks are a prime opportunity for examining children's gestures. For example, children's use of gesture during cardinality tasks, in conjunction with their speech, can be indicative of their readiness to learn new mathematical information (Gunderson et al., 2015; Gibson, Gunderson, Spaepen, Levine, & Goldin-Meadow, 2019). In particular, children appear to use gestures during cardinality tasks when they are asked to create set sizes that are at or just above the quantity they are able to produce (Gordon, Chernyak, & Cordes, 2019). In other words, children may be using gestures during counting to help ease their cognitive load by tracking objects they have already counted. Specifically, gestures provide an external link between the verbal count list and the counted objects in a sequential manner. This practice has led to greater counting accuracy when used by children, as they individuate and tag each item as they count (Alibali & DiRusso, 1999). Furthermore, there is a positive relation between children's number knowledge during a counting task and their use of pointing and counting gestures, such that children with less knowledge about cardinality engage in less serial pointing compared with those with a better understanding of cardinality (Le Corre & Carey, 2007).

Recent work has examined this trend with preschool children's performance on the standard, titrated Give-N task (Gordon et al., 2019). Children's cardinality ability, but not their age, was positively related to their use of spontaneous gestures on this task. Furthermore, children in this study who had not yet mastered the cardinality principle used more gestures on specific parts of the Give-N tasks that involved creating sets of objects they had just learned or were in the process of learning. In other words, children who were in the process of learning how to create sets of four objects could reliably create sets of two or three objects without the help of gesture but tended to use more gestures to create a set of four objects. This suggests that the spontaneous gestures young children employ while learning about cardinality are dynamic and change with their underlying knowledge of the task. However, it is an open question as to why these patterns may emerge. In particular, this study did not include measures of more domain-general abilities such as WM, which may account for additional variation in both the types of gestures and the resulting score on the cardinality task.

Working memory and early math abilities

Although prior work has shown that spontaneous gesture use relates to children's knowledge, it is critical to also consider how differences in children's domain-general abilities such as their WM may affect both their gesture use and their math performance. Early math performance is highly related to general cognitive abilities such as WM (see Bull & Espy, 2006, for a review). WM is limited in capacity (e.g., Cowan, 2001; Miller, 1956), and thus different tasks can be conceptualized as having differing amounts of cognitive "load," such that a task that requires more simultaneous memory and processing would have a higher load (i.e., cognitive load theory; Sweller, 1988; Sweller, Van Merrienboer, & Paas, 1998). In addition to the variation in potential cognitive load, individuals vary in their personal WM capacities. In other words, the more WM capacity individuals have, the better their performance on cognitively difficult tasks (Engle, 2002), including mathematics tasks. For example, prior work shows that children with higher WM capacities have higher accuracy in solving arithmetic word problems (kindergarten to Grade 3; LeBlanc & Weber-Russell, 1996). Furthermore, young children's WM strongly relates to their subsequent scores on standardized math tests (Monette, Bigras, & Guay, 2011) and is an important predictor of their early number skills (Bull & Lee, 2014; Kolkman, Hoijtink, Kroesbergen, & Leseman, 2013). Thus, children with lower WM abilities may have more difficulties in learning about math such as having difficulty in remembering and carrying out instructions, monitoring their own progress in a task, and remembering to use particular strategies.

Gestures and working memory in mathematical contexts

Given the relation between gesture and math, as well as that between WM and math, it is important to consider how gestures and WM may interact. Gestures appear to both affect the demand on WM and have differential benefits depending on the user's WM ability level and current content knowledge (Alibali & DiRusso, 1999; Goldin-Meadow, 2011). For example, gesture can lighten a speaker's cognitive load during problem solving and free up potential WM resources (Goldin-Meadow et al., 2001; Ping & Goldin-Meadow, 2010). Gestures also occur more frequently when task demands are high (Chu & Kita, 2011). Whereas prior work has focused on the relation between gesture and WM, in the current study we were interested in how individuals' WM and their use of gesture may interact in a mathematical environment.

Gestures' positive impact on WM load has been found in both children and adults during math-related tasks (Goldin-Meadow et al., 2001) and a broader array of contexts (Wagner, Nusbaum, & Goldin-Meadow, 2004). Furthermore, the specific *type* of gesture that is used is relevant in its ability to reduce WM load. Cook et al. (2012) asked adult participants to solve math problems, remember a span, and gesture (a meaningful movement), move both hands in circles (a meaningless movement), or not move their hands while explaining their solution to the math problems. Participants who used their natural gestures remembered more of the span than those who engaged in meaningless movements (moving their hands in circles). These findings indicate that meaningful gestures to the task can lighten the speaker's overall WM load during math tasks.

Evidence from studies with adults suggests that there are differential benefits from using gestures during a math task depending on an individual's WM ability. Specifically, Marstaller and Burianová (2013) showed adults a numerical equation on a screen and asked them to judge whether the solution to a mathematical equation was correct. After receiving feedback, the adults were shown a series of random letters before being asked to explain their prior judgment. While providing their explanation, they were either asked to gesture to the screen or not. Lastly, they were asked to recall the letters. Results indicated that individual differences in participants' WM capacity was related to whether gestures would benefit their WM load. Specifically, the instruction to use gestures had a significant, beneficial effect on WM performance, but only for those adults who had a low WM capacity. This suggests that gestures can assist and reduce WM load on a particular task but that it is critical to understand how individuals' WM capacity may affect both their task performance and their use of gesture. However, less is known about the interplay between WM load and capacity for children and whether these may interact with children's gesture use and math abilities.

A separate but related literature suggests that an interdependency among gestures, WM, and math performance exists for young children. Consider again the example of children learning how to count and the underlying required knowledge; they need to hold information in their WM related to cardinality and ordinality (the ordered relation between each number) while simultaneously producing a verbal count list and tracking the objects visually to see whether there are more objects that need to be counted. Gesture helps to overcome some of the burden of these counting procedures by facilitating a more direct external representation of the information. Gesture links the physical objects in space to their more abstract verbal count list (Alibali & DiRusso, 1999). Indeed, prior empirical work supports the idea that representing information externally through gesture lightens the load on an individual's WM (Kirsh, 1995; Kirsh & Maglio, 1994). This in turn frees up WM resources to complete the task and produce the correct number of objects. In summary, WM has been shown to relate to math performance, gesture has been shown to assist with math performance, and gesture allows for a reduction of WM demand. However, prior empirical work has not examined this dynamic relation in young children in the context of early math understanding.

The current study

We began to address this gap by investigating the relations among preschoolers' number knowledge, WM, and spontaneous gesture use. In the current study, we coded preschoolers' gestures during the Give-N task to explore how individual differences in gesture use relate to the link between their WM ability and their performance on the cardinality task. In particular, we sought to address two primary questions in relation to children's gesture use, WM, and number knowledge.

First, we investigated the relations among children's WM ability, cardinality knowledge, and gesture use during the Give-N task. Specifically, we expected to find separate positive relations between children's gesture use and Give-N score, between their WM and Give-N score, and between their WM and gesture use. In particular, we expected that children's pointing and counting gestures, the most task-relevant and conceptually useful gestures, would be the crux of each gesture relation. Second, we examined whether children's gestures affected the relation between their WM and their cardinality knowledge. Here, we predicted that children's spontaneous unprompted gestures would moderate the relation between children's WM ability and their cardinality performance on the Give-N task. Lastly, we conducted an exploratory post hoc analysis to consider whether children's WM capacities may affect their use of spontaneous gesture and performance on the Give-N task. We discuss the implications of our findings, including a discussion of how the results from our low-income sample and modified Give-N methods may compare with previous work from a higher-income sample with a standard Give-N measure (Gordon et al., 2019).

Method

Participants

Participants were 81 preschoolers ranging in age from 3.40 to 5.67 years (M_{age} = 4.75 years; 60% girls). One additional participant was recruited but was not included in the final sample because the child was unable to complete any of the tasks due to limited language production. An a priori power analysis was performed to determine the appropriate sample size via G*Power (Faul, Erdfelder, Lang, & Buchner, 2007). The analysis, including three predictor variables with a medium effect size, α = .05, and $1 - \beta$ power of .85, yielded a projected sample size of N = 87. However, data collection needed to be discontinued unexpectedly in March 2020 due to the global pandemic, resulting in the final sample of N = 81. The majority of the participants (n = 70) were recruited as part of a larger study investigating children's early numerical and executive functioning abilities (Scalise & Ramani, 2021). The remaining participants (n = 11) were recruited to participate in the current study only.

Recruitment took place at four Head Start centers in a mid-Atlantic metropolitan area of the United States. Head Start is a federally funded program for families whose incomes are below the federal poverty guidelines (annual household income of $25,750 or less for a family of four in the year these data were collected). Eleven parents did not complete the parent survey; of the remaining 70 participants, the race of the sample was 54% African American, 10% Caucasian, 9% Asian or Pacific Islander, 1% Native American or Alaskan, and 10% biracial or multiracial (16% of survey respondents did not provide a response to this question). The ethnicity of the responding sample was 26% Hispanic or Latino and 71% not Hispanic or Latino (3% of survey respondents did not provide a response to this question). The parental education of survey respondents was 3% completing less than high school, 4% completing some high school, 24% completing a high school diploma or GED, 24% completing some college coursework or vocational training, 10% completing a 2-year college degree (associate's), 31% completing a 4-year college degree, and 3% completing a postgraduate or professional degree (M.A., Ph.D., M.D., or J.D.).

Procedure

Participants were seen for one visit at the children's school for approximately 15 min. Participants sat either next to the experimenter (a White female) on the floor or across a child-sized table. The visit was video-recorded. The experimenter administered a battery of three tasks in English: two tasks to assess WM and one task to assess cardinality. These tasks were administered in the same order as described below.

Working memory

Children completed a forward word span task and a forward Corsi Block task as measures of their WM. These two tasks were collapsed into a composite WM score, as detailed in Results. Both WM tasks were scored live by the experimenter. Later, a separate research assistant verified the live scores by watching each video and then entering the score into the data sheet.

Forward word span. Children were read a sequence of color words at approximately a rate of one word per second and were asked to repeat those words back to the experimenter in the same order (adapted from Pickering and Gathercole, 2001; Müller, Kerns, & Konkin, 2012 show that similar forward span tasks have "good retest reliability" with preschoolers, intraclass correlation coefficient [ICC] = .56, $p < .05$). The number of color words within a trial ranged from two to seven, with 2 trials at each span level (2 trials of two, 2 trials of three, etc.). The first 2 trials were practice trials with a string of two color words (e.g., green, blue) with feedback. The experimenter ended the task if the participant incorrectly answered both trials of a particular span. The dependent measure was the highest span that children were able to recall correctly.

Forward Corsi Block. Children were presented with a tablet version of the forward Corsi Block task (Ramani et al., 2020; adapted from Corsi, 1972). Previous research that has used similar forward Corsi block tapping tasks with preschoolers reported high reliability (e.g., a nontablet version shows a high test–retest reliability, using Pearson correlations, of $r = .83$ with preschool-aged children; Alloway, Gathercole, & Pickering, 2006). The tablet (LENOVO tablet with a screen size of 25.7 cm measured diagonally) displayed a picture of a pond with an animated frog "jumping" onto different lily pads (Fig. 1). Children were instructed to tap on the lily pads in the same order that the frog jumped on them. The task began with a two-span practice trial with corrective feedback (happy face or sad face). If children got the first practice trial wrong, they were given another practice trial with additional corrective feedback. If they got the practice trial right, they moved on to test trials with no feedback. The trials increased in span size each time children got two of the same span size correct. For each trial, children received 1 point for every lily pad they accurately recalled (2 points for a two span, 3 points for a three span, etc.). This allowed for partial scores on longer trials that are more difficult for children to remember the whole span rather than using the less variable measure of the longest span they could remember with complete accuracy. Thus, the dependent measure was the total points they achieved.

Cardinality

Modified Give-N. Children were asked to place sets of ducks from a pile of 12 ducks into a blue basket or "pond" (adapted from Krajcsi, Fintor, & Hodossy, 2018).[1] The experimenter asked for sets from 1 to 8 in a predetermined randomized order generated from a random number generator prior to the start of data collection: 1, 5, 3, 8, 4, 7, 2, 6. Children were asked for each set size three times in the same randomized list order for a total of 24 trials regardless of their response. The alpha coefficient for the 24 trials was .93, suggesting high internal consistency for this task. Accuracy for each trial could be assessed as a proportion of trials correct (0/3, 1/3, 2/3, or 3/3). The dependent measure was children's knower level, which was defined, for the purposes of this study, as when all trials including and below a particular set size are above chance (2/3 or 3/3) and the trial immediately after in the count list is below chance (0/3 or 1/3). This task was scored live, trial by trial, by the experimenter. Later, a separate research assistant verified the accuracy of each trial by watching each video and then entering the score into the data sheet.

Transcription and coding

All speech and gestures from the videotaped modified Give-N task were transcribed by research assistants trained to transcribe reliably using the CHAT conventions of the Child Language Data Exchange System (CHILDES; MacWhinney, 2000). Transcription reliability was assessed by having a second reliable coder provide verification and agreement on the speech and gesture decisions.

[1] The portion of our sample who were recruited for a larger study ($n = 70$; Scalise & Ramani, 2021) also completed the standard Give-N assessment in a separate visit. To compare the similarity between these measures, all children who received a knower level of 7 or 8 in the adapted version were recoded as having a knower level of 6, to maintain consistency in knower level assignment for the standard measure. Next, a Pearson's product–moment correlation was run between the recoded adapted knower level scores and the standard knower level scores, showing a strong positive relation, $r(68) = .828$, $p < .01$. This indicates that the adapted measure provides a consistent measure of cardinality knowledge compared with the standard measure, with the added benefit of controlling for the total number of trials children received.

Fig. 1. Still image from adapted Corsi Block task.

Measures

Children's gestures. Each child's transcript was divided into sections based on the numerical trial and then coded for specific behaviors from three categories. The primary behavior of interest was *m*ath-specific gestures (Table 1), divided into pointing and counting gestures, and other math gestures, specifically fingers held up and magnitude (adapted from Gordon et al., 2019). All transcripts were coded for the behaviors of interest by one primary coder. A second reliable coder coded 21% of the transcripts for the same behaviors of interest, with an inter-rater reliability of 82.35% for pointing and counting gestures and 100% for the other gestures.

Pointing and counting gestures were coded as a singular unit (e.g., pointing and counting to six items was equal to one instance of a pointing and counting gesture). All pointing and counting gestures were coded as one unit of gesture regardless of whether the gestures occurred with speech, whether participants were touching the object as they counted, whether the gesture itself was correct (i.e., correct if one-to-one correspondence with each object), and whether participants' verbal count list was correct. Other math gestures consisted of two primary gesture types. First, children would hold up a particular quantity of fingers in order to represent a specific quantity. Second, children would indicate information regarding magnitude by making a pointing or waving gesture to a set of objects and pairing that gesture with a verbal statement regarding the magnitude of a set. Critically, we did not differentiate between gestures that did and did not co-occur with speech. In other words, any instance of hand gestures that could be recognized under our coding scheme were included in our analyses.

Children's speech. Whereas all instances of gesture regardless of speech were coded, one measure of children's speech during the modified Give-N task was extracted from the transcripts for use as a control variable. Word tokens, or the total numbers of words children said during the task, was extracted as a measure of the overall amount of speech (M = 142.99, SD = 129.80). Given the ample literature suggesting that children's verbal language and gestures are intertwined from infancy (e.g., Iverson & Goldin-Meadow, 2005), we included this variable as a control in our subsequent analyses in order to account for the possibility that children who were more talkative were naturally more likely to gesture.

Results

All analyses were performed using R (R Development Core Team, 2011). There were no significant correlations between children's gender and any other variables (knower level, pointing and counting, age, and WM measures; all p values > .05), and so all further analyses were collapsed across boys and girls.

Table 1
Math-specific gesture definitions and behavioral examples.

Gesture type	Definition	Example
Pointing and counting	Using their finger(s) or hand to indicate objects while verbally producing a count list	Experimenter: "Is that three ducks?" Child: "One, two, three." *[Uses pointer finger to point to the first duck, then the second duck, and then the third duck in the pond.]*
Fingers held up	Any finger configuration on one or both hands that is meant to convey a number/quantity	Experimenter: "Can you put two ducks in the pond?" Child: "This many?" *[Holds up pointer and middle finger to indicate the number two.]*
Magnitude	Pointing and/or circling, waving, or any similar hand gesture referencing a grouping of objects while also talking about the magnitude, quantity, or total number of objects in the set	Experimenter: "Can you put three ducks into the pond?" Child: "..." *[Picks up set of three ducks and dumps in pond.]* "Three!" *[Waves hand over pond with palm down to indicate the set.]*

WM measures

The mean score on the word span task was 3.31 (SD = 1.24) with a range of 0–6. The mean score for the touch base assessment was 6.68 (SD = 6.14) with a range of 0–30. These measures of WM were positively correlated, $r(79) = .31$, $p = .005$. Thus, the scores were combined into a composite measure of children's WM. A z score was calculated for each measure, and then an overall composite was calculated by averaging the two z scores.

Gestures by type

In total, 63% of children (n = 51) used at least one math gesture during the Give-N task for an overall total of 320 gestures used across all children. Of this total, 275 gestures were pointing and counting (86%), 25 gestures were fingers held up (8%), and 20 gestures were magnitude related (6%). On average, children used 3.94 gestures (SD = 4.83) with a range of 0–20 (Table 2).

In addition, we were interested in how each of these gestures was used by children of different knower levels. In particular, we wanted to know whether our findings using the adapted Give-N method produced similar types and rates of gesture seen within other versions of the Give-N task from previous literature (Gordon, Chernyak, & Cordes, 2019); see Table 3 for a breakdown of gesture type by knower level). The distribution of gestures in our study is consistent with that of prior literature, where pointing and counting gestures dominated the overall total of spontaneous gestures employed by children in a cardinality task. Given the low frequency of the second and third gesture types, and to maintain consistency with the prior literature, fingers showing numbers and magnitude gestures were collapsed into one variable, namely other gestures.

Are children's WM ability, cardinality knowledge, and gestures related?

To investigate the relations among variables, Pearson's product–moment correlations were calculated among children's age, word tokens, pointing and counting gestures, other math gestures, knower level, and WM composite (Table 4).

We found child age was positively correlated with knower level and WM composite. Children's word tokens, or the amount of speech children used in the Give-N task, were positively correlated with their pointing and counting gestures, WM composite, and knower level. There was a strong positive correlation between knower level and WM composite. Children's pointing and counting gestures had a significant positive relation with their age, knower level, and WM composite; however, the other math gestures variable was not correlated with any variables of interest. Therefore, all subsequent analyses were run with pointing and counting gestures as the sole gesture variable; however, each analysis was also run with a composite of all math gestures, including both pointing and counting and other math gestures combined, and the pattern of results was the same.

Table 2
Descriptive statistics of individual children's use of gesture broken down by gesture type.

	M	*SD*	*Min*	*Max*
Pointing and counting gestures	3.40	4.59	0	18
Fingers showing numbers gestures	0.31	0.89	0	5
Magnitude gestures	0.25	0.60	0	2
Total gestures	3.94	4.83	0	20

Table 3
Numbers and percentages of children who used gesture.

		Pointing and counting		Fingers showing numbers		Magnitude	
Knower level	*N*	*n*	%	*n*	%	*n*	%
0	2	1	50	0	0	0	0
1	9	0	0	2	22	0	0
2	18	6	33	4	22	6	33
3	5	0	0	0	0	0	0
4	1	1	100	0	0	1	100
5	3	1	33	0	0	0	0
6	5	3	60	0	0	0	0
7	1	1	100	0	0	0	0
8	37	30	81	6	16	6	16

Table 4
Descriptive statistics and correlations among age, word tokens, gestures, working memory, and knower level.

Variable	*M*	*SD*	1	2	3	4	5
1. Age	4.75	0.59					
2. Word tokens	142.99	129.80	.10				
3. Pointing and counting gestures	3.40	4.59	.28*	.57**			
4. Other math gestures	0.56	1.05	−.13	.19	.16		
5. Working memory composite	0.00	0.81	.56**	.24*	.24*	−.07	
6. Knower level	5.09	3.00	.66**	.26*	.45**	−.19	.62**

* $p < .05$.
** $p < .01$.

To better understand how children's pointing and counting gestures, as well as their WM composite, may affect their performance on the Give-N task, we conducted three partial correlations while controlling for age. Consistent with prior literature (Gordon et al., 2019), pointing and counting gestures were positively correlated with knower level, $r(81) = .36$, $p < .01$. Furthermore, knower level was also positively correlated with WM composite, $r(81) = .40$, $p < .001$. However, the correlation between pointing and counting gestures and WM composite (Table 4) was no longer significant when age was controlled, $r(81) = .10$, $p = .385$. Thus, children's knower level was correlated with their pointing and counting gestures as well as their WM composite after controlling for age. However, pointing and counting gestures were no longer correlated with WM composite.

To account for the possibility that children who use more speech are more likely to gesture, we conducted three partial correlations while controlling for word tokens. Even while controlling for amount of speech, pointing and counting gestures were positively correlated with knower level, $r(81) = .38$, $p < .01$, and knower level was positively correlated with WM composite, $r(81) = .59$, $p < .001$. The correlation between pointing and counting gestures and WM composite was not significant while controlling for word tokens, $r(81) = .13$, $p = .263$. Thus, children's knower level was correlated with their pointing and counting gestures as well as their WM composite after controlling for the total amount of speech.

Do gestures moderate the relation between WM ability and cardinality?

Next, we tested the hypothesis that pointing and counting gestures moderate the association between children's WM composite and their knower level while controlling for age using multiple regression analysis. Step 1 included age and the main effect of WM composite, Step 2 included the main effect of pointing and counting gestures, and Step 3 included the interaction between WM composite and pointing and counting gestures. The overall model was significant, $F(4, 76) = 27.95$, $p < .001$, accounting for 60% of the variance in children's knower levels. There were significant main effects for WM composite ($\beta = 1.46$, $t = 4.01$, $p < .001$), pointing and counting gestures ($\beta = 0.18$, $t = 3.56$, $p < .001$), and age ($\beta = 2.04$, $t = 4.50$, $p < .001$). However, the interaction term between WM composite and pointing and counting gestures was not significant ($\beta = -0.14$, $t = -1.49$, $p = .14$).

Does children's WM affect their gestures and performance on the Give-N task?

Although our regression analysis found that the WM composite did not significantly moderate the relation between gestures and knower level in our sample, we conducted a series of post hoc exploratory analyses to lay the groundwork for hypothesis building for future studies with more power to detect significant interaction effects. To gain a descriptive exploratory understanding of the relations between gestures and WM in early mathematical contexts, we followed Marstaller and Burianová's (2013) protocol to explore patterns of gesture use within groups of individuals with different WM capacities. Thus, we used the median WM composite score (−0.02) to divide the participants into two groups: children with low WM ability ($n = 36$) and those with high WM ability ($n = 45$). Low-WM children used on average 1.89 gestures ($SD = 3.83$), whereas high-WM children used on average 4.60 gestures ($SD = 4.83$). We then looked at the relation between children's pointing and counting gestures and their subsequent knower level in the two WM groups separately. Thus, two post hoc multiple regression analyses were used to test whether children's gestures significantly predicted their knower level while controlling for age. The first analysis was run solely with low-WM children; the overall regression was significant, and the two predictors explained 52.31% of the variance, $F(2, 33) = 18.10$, $p < .001$. We found that use of pointing and counting gestures significantly predicted low-WM children's knower level ($\beta = 0.35$, $p < .001$), as did age ($\beta = 2.11$, $p < .01$). The second regression analysis included only high-WM children; the overall regression was significant, with the two predictors explaining 31.12% of the variance, $F(2, 42) = 9.49$, $p < .001$. However, high-WM children's use of pointing and counting gestures was not a significant predictor of their knower level ($\beta = 0.09$, $p = .192$), although age was significant ($\beta = 2.86$, $p < .001$). Fig. 2 shows a scatterplot of the relation between pointing and counting gestures and knower level by WM group (low or high).

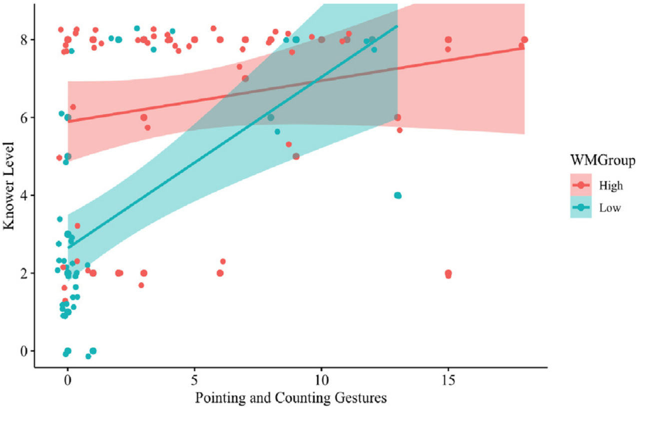

Fig. 2. Jittered scatter plot with pointing and counting gestures predicting knower level by median split working memory (WM) group.

Discussion

There were two primary goals of this study. First, we sought to investigate how children's gesture use, WM, and cardinality knowledge related to each other. Second, we tested our hypothesis that children's gestures moderated the relation between children's WM ability and their performance on the Give-N cardinality task. In addition to these main objectives, we report exploratory post hoc analyses related to how children of different WM levels may use gestures differently on cardinality tasks.

Our first goal was to provide an assessment of the relations among children's gesture use, WM, and cardinality knowledge. In the current study, we found that more than half of the children used gestures while completing the cardinality task, and the majority of these gestures used were pointing and counting the objects. We also found a positive relation between children's performance on the cardinality task and their use of these gestures, which is consistent with prior literature (Gordon et al., 2019). Additionally, these relations were not explained by children's age or how much they talked during the task. Our findings extend prior work in three novel ways. First, by the inclusion of children's WM, we were able to investigate how these variables may be interrelated during early childhood. Specifically, preschool-aged children's knower level was related to both their pointing and counting gestures and their WM while controlling for age. However, these children's pointing and counting gestures were not significantly related to WM while controlling for age. Second, our results with a low-income sample showed the same positive significant relation between preschool-aged children's gestures and their knower level that was reported with higher-income children by Gordon and colleagues (2019). This finding is of particular interest given previous findings showing that low-income students perform below their mid-income peers on mathematical tasks, but these trends do not persist in nonverbal numerical tasks (Jordan, Huttenlocher, & Levine, 1992; Jordan, Levine, & Huttenlocher, 1994). Whereas previous studies in the domain of mathematics have shown that young children's performance on nonverbal numerical tasks is equivalent regardless of income background (Ginsburg & Russell, 1981; Jordan et al., 1992, 1994), our study suggests that similar expectations could be held for children's use of gesture within numerical tasks as well. Finally, our study extends previous work in an important way by using a different nontitration version of the Give-N task (adapted from Krajcsi et al., 2018). This is critical because it shows that neither children's gesture use nor their explicit task knowledge is directly tied to the $n + 1$ titration format; rather, their performance on the task and their gesture use are instead based on their implicit knowledge and the level of difficulty of each individual trial.

Our second goal tested the hypothesis that children's gestures moderated the relation between their WM ability and their cardinality performance on the Give-N task. Our hypothesis was based on the ample literature suggesting that children's WM is related to their math ability and that gestures can reduce WM load (Goldin-Meadow, 2011). However, our analyses showed that there was not a significant interaction between children's WM and their gesture use on their knower level in our sample. There are several reasons why this may be the case. First, it is possible that the interplay between gesture use and WM was not actually captured in the cardinality task used in the study. Our study examined only children's spontaneous unprompted gestures. For children to use these gestures, they would first need to have enough WM resources to remember to employ gestures in the first place. Even if children with lower WM used gesture, their efficacy and cognitive benefit in the math context is still in question. In our sample specifically, many of the children with lower WM did not use gesture at all, which makes assessing any potential relationship between gesture and knower level difficult to tease out. Thus, future work with a larger sample would likely have more variability in lower-WM children's gesture use and in turn would give more power to detect the hypothesized (small) interaction effect.

Furthermore, although it is possible that children could overcome some of the limits of their WM using gestures, here we were expecting them to gesture spontaneously without any instruction. Thus, future research could consider the possibility that providing young children with directions to use a specific gestural strategy, such as pointing and counting, may also change the relation among children's current WM load, capacity, and math ability. Finally, our results could be limited by our sample size. As noted in Method, our proposed sample size was determined using an a priori power analysis that included three predictor variables. However, in our final analyses, we chose to include a fourth variable as a covariate (age), and our data collection was stopped unexpectedly before reaching our predetermined sample size. It is possible that the interaction between gesture and WM was occluded because our study may have been underpowered. Future studies considering gesture as a moderator should consider a larger sample size in order to uncover any potential interaction effects.

Lastly, we reported exploratory post hoc analyses to consider patterns between pointing and counting gestures and knower level within high- and low-WM groups. Based on the regressions and the visualization within the scatterplot, we would hypothesize that future research with a larger sample of children might see a significant relation between gesture and knower level for lower-WM children, with less of a relation between gesture and knower level for higher-WM children. If this pattern of results is upheld in future research, it would imply that children who have higher WM might not necessarily need to rely on an external strategy such as gesture to lower the cognitive demand during the task because they already have enough mental resources to solve the problem. However, further empirical research must be conducted before any conclusions are drawn related to this complex relation.

In sum, children from low-income backgrounds use gestures in similar types and rates in a nontitrated version of the Give-N task compared with children from higher-income backgrounds in prior work using a standard Give-N task. Furthermore, children's use of gesture is positively related to their performance on this task (knower level) above and beyond the impacts of their age and how much they talked during the task. Children's knower level also was positively related to their WM while controlling for age. However, no significant relation between children's gesture use and their WM was found while controlling for age. Although we did not find evidence for the hypothesized moderation model, we did find that both children's gesture use and their WM were significant predictors of children's performance on the cardinality task, suggesting that both play an important role in children's early numerical knowledge. Given prior work highlighting that quantitative abilities are predictive of later mathematical abilities (Chu, vanMarle, & Geary, 2015; Feigenson, Libertus, & Halberda, 2013; Geary & vanMarle, 2016; Starr, Libertus, & Brannon, 2013), it is of particular importance to understand how both domain-specific and domain-general factors affect children's early math learning. Here, we provide additional evidence that there are nuanced relations among children's early math learning, WM, and use of gesture strategies.

Although the current study did not test for causal relations among gesture, math, and WM, the results indicate that future work on children's mathematical abilities and learning should take each child's WM ability and gestures into consideration. Consistent with prior work suggesting that gestures can help to alleviate demands on WM (Cook et al., 2012), future work should take into consideration the dynamic relation of these variables. In particular, new experimental studies could consider how individual differences in children's WM and math ability relate to their use of gestures and how this may relate to gesture as an effective tool for learning.

A further line of inquiry may consider how these relations change across time. For example, as children grow older and learn new mathematical concepts, their WM resources and how they are applied to different settings also change (Case, 1985; Case, Kurland, & Goldberg, 1982; Halford, 1993). The current study considered only one domain of mathematics within a small age range during early childhood. Thus, the relations found in the current study may change as children's WM ability changes and their knowledge of cardinality grows.

Furthermore, little is known about external factors that may increase or decrease children's use of gesture in a math context. The current study investigated only the internal factors that may affect children employing these gestures spontaneously (i.e., math ability and WM) but did not provide any assessment of what types and rates of cardinality-related gestures are currently being modeled to children by their teachers, parents, or even peers.

Lastly, there are a number of open questions related to how gestures may be used in math contexts where mastery of the content has already been reached. Although children could be labeled cardinal principle knowers based on their success in the Give-N task used in this study, there is still room for future research considering whether children may still use gestures and, if so, whether these gestures relate to domain-general functions such as WM.

Overall, we found that children's use of gestures in a cardinality task, number knowledge, and WM abilities are interrelated. The overall patterns of relations between gesture and number knowledge with low-income preschoolers is comparable to those found in previous literature with higher-income preschoolers. The descriptive patterns imply that future research could consider potential moderations between children's WM and gesture use on their math knowledge. Thus, children's domain-specific and domain-general abilities may be intertwined with their use of gestures.

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