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Brief article

The gestures ASL signers use tell us when they are ready to learn math

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ABSTRACT

The manual gestures that hearing children produce when explaining their answers to math problems predict whether they will profit from instruction in those problems. We ask here whether gesture plays a similar role in deaf children, whose primary communication system is in the manual modality. Forty ASL-signing deaf children explained their solutions to math problems and were then given instruction in those problems. Children who produced many gestures conveying different information from their signs (*gesture-sign mismatches*) were more likely to succeed after instruction than children who produced few, suggesting that mismatch can occur within-modality, and paving the way for using gesture-based teaching strategies with deaf learners.

1. Introduction

It is well known that speakers gesture when they talk (McNeill, 1992). Moreover, it is known that co-speech gestures can convey substantive information not found in a speaker's words (Goldin-Meadow, 2003). Finally, it has been shown, across a variety of tasks, that speakers whose gestures convey different information from the information conveyed in speech—*gesture-speech mismatch*es—learn more from instruction than speakers whose gestures convey the same information as speech (Church & Goldin-Meadow, 1986; Perry, Church & Goldin-Meadow, 1988; Pine, Lufkin & Messer, 2004).

Gesture-speech mismatches juxtapose two different ideas within a single response. The juxtaposition of two ideas highlights their discrepancy, and increased discrepancy has been found to motivate a search for additional information relevant to a particular task (Brinol, Petty & Wheeler, 2006; Rydell, McConnell & Mackie, 2008). However, there is another discrepancy inherent in gesture-speech mismatches—the manual vs. spoken modality. Previous research has shown that conveying two different ideas across two modalities, one in the spoken modality and a different one in the manual modality, can predict learning better than conveying two different ideas entirely within the spoken modality, either within the same spoken explanation or across explanations (Church, 1999). We ask here whether juxtaposing two different ideas within a single modality—the manual modality—is sufficient for mismatch to predict increased learning. We turn to deaf individuals who use sign as their primary language to address this question.

Deaf signers have been found to gesture when they sign (Emmorey, 1999; Sandler, 2009), but, of necessity, their gestures are produced in the same (manual) modality as their signs. If juxtaposing different ideas across two modalities is essential for mismatch to predict learning, then mismatch between sign and gesture (i.e., mismatch within one modality) should *not* predict learning in signers, unlike mismatch between speech and gesture (i.e., mismatch across two modalities), which does predict learning in speakers. Alternatively, it may be the representational format within which different ideas are conveyed that is responsible for

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mismatch predicting learning. If so, juxtaposing different ideas across two distinct representational formats regardless of modality—for example, an analog format underlying gesture vs. a discrete, segmented format underlying words (Kendon, 1980; McNeill, 1992) or signs (Klima & Bellugi, 1979; Liddell, 2000; Liddell & Metzger, 1998)—should be key to highlighting discrepancy. Mismatching gesture should then predict learning in signers as well as speakers.

2. Method

2.1. Participants

Forty-nine children, ages 9–12, were tested at four regional Schools for the Deaf. We focused on the 40 children who did not know how to solve mathematical equivalence problems (see below): 37 solved no pretest problems correctly, three solved only one (mean age = 9.9 years, SD = 0.92; 22 girls). All were deaf (30 born to deaf parents, 10 to hearing parents) and all used American Sign Language (ASL) as their primary language.

2.2. Procedure

Both experimenters were fluent in ASL (either native or near-native). Experimenter 1 gave each child a paper-and-pencil pretest containing six problems of the following type (Perry et al., 1988): $6 + 5 + 8 = \_\_ + 8$. Children then explained their pretest solutions in ASL to the experimenter at a whiteboard. Their responses were videotaped and later coded.

Experimenter 2 (MH) then put a new problem on the board and, without putting an answer in the blank or signing the correct answer, taught the child in ASL how the problem could be solved using the equivalence strategy:

YOU DO++ FIND ANSWER. PUT-THERE$_{\text{[blank]}}$ #SO [sweep/point to right side of equation] WILL EQUAL [sweep/point to left side of equation][1]

"What you need to do is to find the answer that fits in the blank so that this side (point to right side of equation) becomes equal to this side (point to left side of equation)."

The problem was then erased and the child was given a new problem to solve. After the child put an answer in the blank, the experimenter asked her whether the two sides of the equation were equal. If the child signed "yes," the experimenter moved onto a new problem; if she signaled "no," the experimenter asked the child for a number that would make the two sides equal and then, no matter what answer the child gave, moved onto the next problem. Four training items were given in all, two on which the experimenter provided the equivalence strategy; two on which the child attempted a solution.

Experimenter 1 then gave the child a posttest comparable to the pretest.

[1] The plus signs indicate reduplication, here highlighting the topic, "What you need to do is…." The pound sign indicates a fingerspelled loan sign (the letter S followed by the letter O). The experimenter produced two hand movements that would be coded as gestures in our system: (1) the PUT sign, which was placed in the blank, would be counted as containing both lexical and gestural information; (2) the index finger sweeps under each side of the equation would be counted as gestures.

2.3. Coding pretest explanations

2.3.1. Categorizing hand movements into signs and gestures

In previous studies of mathematical equivalence in hearing children (Alibali & Goldin-Meadow, 1993; Perry et al., 1988), the sound was turned off to code gesture and the picture was turned off to code speech. Distinguishing gesture and sign was considerably more difficult in this data set since both are produced in the manual modality. All responses were coded twice, once by a gesture coder with no knowledge of ASL trained to code mathematical equivalence, and once by a trained sign coder. We used the following criteria for classifying manual movements as signs and gestures: *Signs* were hand movements that were recognizable signs in ASL and can be found in an ASL dictionary (e.g., Stokoe, Casterline, & Croneberg, 1965), e.g., SEVEN, ADD. *Gestures* were hand movements that are not lexical ASL signs and resemble the gestures hearing children produce on this task (Alibali & Goldin-Meadow, 1993; Perry et al., 1988), e.g., V-hand held under two numbers, signaling that the numbers should be "grouped" and added; palm covering a number, signaling "take away" the number.

All points to the board were considered gestures.[2] However, at times, a child's signs could not be fully interpreted without considering the points that accompanied those signs. For example, the sign ADD produced in space, followed by points at two numbers on the board, is an unclear statement unless the points, which indicate which numbers should be added, are considered. Such sentences in sign are comparable to spoken sentences requiring gesture to clarify the particular referents in the sentence, e.g., "I added this, this, and this." We included points in our analyses of the strategies expressed in sign whenever they were needed to clarify referents (100, 42% of explanations).

Some hand movements could not be uniquely classified as either sign or gesture but rather contained components of each. For example, when a child produces the sign SEVEN over the numeral 7 on the board, the shape of the hand conveys "7" in sign and the location of the hand (at the 7) conveys "7" in gesture (see second and third examples in Fig. 1). We included hand movements of this sort in both analyses (59, 25% of explanations), using handshape information in the sign analysis, and location information in the gesture analysis.

2.3.2. Coding problem-solving strategies in signs and gestures

We then coded the children's explanations using a system developed to describe the problem-solving strategies hearing children produce on this task (Perry et al., 1988). For each explanation, the sign coder determined which problem-solving strategies were expressed in sign in that explanation, and the gesture coder did the same for gesture (see Table 1). Explanations that could not be categorized as one of the strategies in Table 1 were considered "uncodable" (15% of explanations in sign, 16% in gesture). Uncodables

[2] Note that points can serve as pronouns in sign language. A point at an abstract referential space would have been considered a sign in our coding system, but none were produced (the children did, however, point at themselves, which was coded as the pronoun "I").

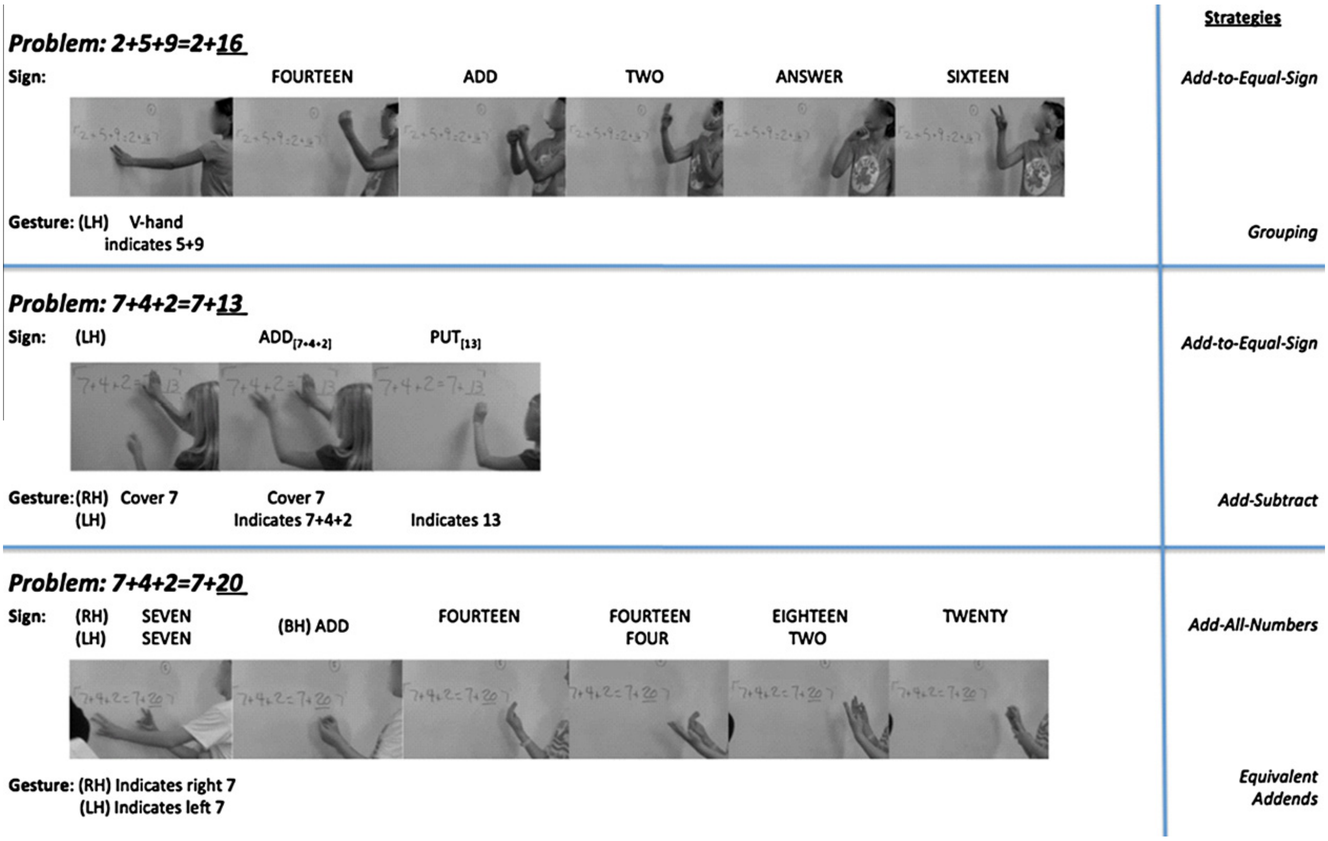

Fig. 1. Examples of sign-gesture mismatches. The line above each example gives glosses for the signs; the line below gives glosses for the gestures. In the first example, the child produces the (incorrect) "add-to-equal sign" strategy (FOURTEEN, ADD, TWO, ANSWER, SIXTEEN) in sign, and produces a gesture highlighting the two unique numbers on the left side of the equation (5 + 9), thus conveying the (correct) "grouping" strategy (i.e., group and add 5 and 9) in gesture. In the second example, the child produces the (incorrect) "add-to-equal sign" strategy (ADD$_{7+4+2}$, PUT$_{13}$) in sign and produces gestures conveying the (correct) "add-subtract" strategy (cover = take-away 7, 7 + 4 + 2, 13) in gesture. The first movement produced by the left hand in this example (see the second panel) is a lexical item in ASL and is therefore considered a sign (ADD); the fact that the hand is placed on the board over a set of numbers provides gestural information about the numbers to be added (i.e., the numbers on the left of the equal sign). As a gesture, the hand movement is interpreted in the context of the second gesture in the string, the "take-away-7" gesture, turning the gesture string into an "add-subtract" strategy; i.e., add 7, 4, and 2, subtract 7. In the third example, the child produces the (incorrect) "add-all-numbers" strategy (SEVEN - SEVEN, ADD, FOURTEEN, FOURTEEN - FOUR, EIGHTEEN - TWO, TWENTY; i.e., add 7 and 7 to get 14, add 4 more to get 18, add 2 more to get 20) in sign and produces gestures highlighting a subset of these numbers (7–7), thus conveying the (correct) "equivalent addends" strategy (i.e., the two numbers found on both sides of the equation) in gesture.

Table 1
Examples of problem-solving strategies in sign and in gesture produced in the pretest explanations. The math problem eliciting these explanations is: 4 + 6 + 9 = __ + 9.

Problem-solving strategy	Example in sign	Example in gesture
Correct explanations		
Add–subtract	FOUR PLUS SIX EQUAL TEN, PLUS NINE EQUAL NINETEEN, SUBTRACT NINE EQUAL TEN	Sweep under the 4, 6 and left 9, pause, grab under the right 9, point at the blank
Equivalence	ADD-ADD-ADD$_{[4+6+\text{left }9]}$, ANSWER NINETEEN, ADD$_{[\text{blank}+\text{right }9]}$, ANSWER NINETEEN, SAME	Left hand index sweep at the left 9, 6, and 4, pause, right hand index sweep at the blank and right 9
Equivalent addends	NINE$_{[\text{left }9]}$, NINE$_{[\text{right }9]}$, SAME	A left hand index point at the left 9 with a simultaneous right hand index point at the right 9
Grouping	SIX FOUR ADD, ANSWER TEN	A "V" point below the 4 and the 6, pause, point at the blank
Incorrect explanations		
Add-all-numbers	FOUR PLUS SIX EQUAL TEN, PLUS NINE EQUAL NINETEEN, PLUS NINE EQUAL TWENTY-EIGHT	Index point at 4, 6, left 9, right 9 and the blank
Add-to-equal sign	SIX FOUR ADD, ANSWER TEN, NINE ADD, ANSWER NINETEEN	Index point at the 4, 6, left 9 and the equal sign
Carry	FOUR$_{[\text{in blank}]}$ FROM FOUR$_{[\text{on left}]}$	Pinch at the 4 and drag to the blank
Wrong grouping	SIX NINE ADD, ANSWER FIFTEEN	A "V" point at the 6 and the left 9, a pause, an index point at the blank

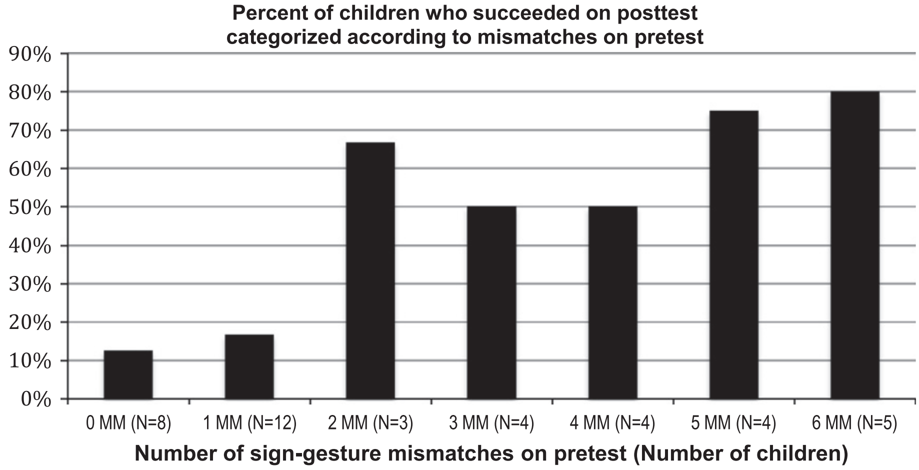

Fig. 2. Percent of children succeeding on posttest as a function of the number of mismatches the children produced on pretest.

were imprecise (e.g., ADD produced in space without disambiguating points); an uninterpretable selection of numbers (e.g., point at 2 and point at 4 on right in 2 + 6 + 4 = __ + 4); numbers that were not in the problem and could not be derived by adding or subtracting numbers that were (e.g., THIRTEEN in 2 + 6 + 4 = __ + 4); or idiosyncratic strategies (e.g., multiplying numbers, adding numbers from previous problems, etc.).

2.3.3. Coding gesture-sign mismatches

We focused on explanations that contained both gesture and sign to determine *gesture-sign mismatches*. An explanation that conveyed in gesture a different strategy from the strategy conveyed in sign was considered a mismatch (see examples in Fig. 1). Explanations in which both sign and gesture were uncodable ($N = 13$, 5% of all explanations) were not considered mismatches, nor were explanations containing sign and no gesture (47, 20% of all explanations). However, following Perry et al. (1988), we did consider explanations in which either sign or gesture conveyed an identifiable strategy and the other vehicle conveyed an uncodable strategy to be mismatches ($N = 22$, 23% of mismatches).[3]

Children were then categorized according to the number of explanations containing mismatches that they produced on the pretest.

2.3.4. Reliability

A second speaker proficient in coding gesture in hearing children (and not a signer) coded 25% (60/240) of the data to establish reliability for gesture; a deaf native signer, trained in math coding, did the same for sign. Inter-rater agreement was high for identifying hand movements as gestures or signs (94% agreement between coders for gesture, 90% for sign), and for identifying strategies in gesture or sign (Cohen's kappa = .93 for gesture, .89 for sign). The speaker then coded the strategies in each explanation to determine reliability for gesture-sign mismatch (Cohen's kappa = .84).

3. Results

All 240 of the explanations children produced (6 problems $\times$ 40 children) contained signs; 193 (80%) also contained gestures. Moreover, 40% of the 240 explanations (50% of the 193 explanations containing gesture and sign) were classified as mismatches.

We categorized children according to the number of explanations containing mismatches that they produced on the pretest (out of 6): no mismatches ($N = 8$ children), 1 mismatch ($N = 12$), 2 mismatches ($N = 3$), 3 mismatches ($N = 4$), 4 mismatches ($N = 4$), 5 mismatches ($N = 4$), 6 mismatches ($N = 5$).

Finally, we examined children's performance on the posttest: nine children solved all six posttest problems correctly, 6 solved 5, 1 solved 4, and 24 solved no posttest problems correctly. As this distribution was bimodal, we took four or more problems solved correctly as the criterion for posttest success (recall that no problems were solved correctly on the pretest, except for the three children who each solved 1 correctly[4]). We then calculated the proportion of children who were successful on the posttest as a function of the number of mismatches they produced on the pretest (Fig. 2).

We performed a binary logistic regression using posttest success as the dependent variable; age, sex, family status (deaf parents vs. hearing parents), and number of mismatches on pretest (0–6) as independent factors. A Hosmer–Lemeshow test revealed an overall high goodness-of-fit, χ^2 (8) = 7.81, $p = .45$, suggesting that the model fit the data well. Number of pretest gesture-sign mismatches significantly predicted posttest success, $\chi^2(1, N = 40) = 6.06$, $p = .014$ (see Table 2 for details of the regression analysis). To calculate an effect size, we compared the estimated performance (based on the model) of participants who produced no mismatches on pretest with the estimated performance of those who produced six mismatches on pretest. Participants with no pretest

[3] If we eliminate these 22 mismatches from the analyses (i.e., we do not count them as mismatches), number of mismatches is still a significant predictor of improvement on posttest, $p = 0.01$.

[4] If these three children are eliminated from the analyses, number of mismatches is still a significant predictor of improvement on posttest, $p = 0.013$.

Table 2
Results of the logistic regression analysis exploring the relation between pretest mismatch on posttest success.

	β	S.E.	Wald's χ^2	*df*	*p*	e^{β} (odds ratio)
Sex	.633	.853	.551	1	.458	1.883
Age	.025	.446	.003	1	.956	1.025
Group[a]	2.022	1.267	2.546	1	.111	7.554
Mismatch[b]	.541	.220	6.059	1	.014	1.719
Constant	−3.998	4.245	.887	1	.346	.018

[a] Group = Deaf children born to deaf vs. hearing parents. Because deaf children of hearing parents often learn sign language later in life than deaf children of deaf parents, they might be expected to do less well on a task that involves explanation; however, we found no evidence to support this possibility in our data.

[b] Mismatch = Number of mismatches produced on pretest (0 through 6).

mismatches had a 1.8% chance of improving on the posttest, compared to 32.0% for participants with six mismatches—an effect size of 30.2% (the difference between the two estimated performances).[5] Thus, the more gesture-sign mismatches children produced on pretest, the more likely they were to succeed on posttest. No other factor was statistically significant in predicting success after instruction.

Previous studies of mismatch in hearing children (e.g., Perry et al., 1988) have examined posttest success as a function of mismatch taken as a categorical variable (mismatchers produced three or more gesture-sign mismatches on the pretest; matchers produced fewer than three). Using this approach, we found that 11 of 17 mismatchers (65%) succeeded on the posttest, compared to 5 of 23 matchers (22%), *p*=.0009, Fisher's Exact Test, confirming that mismatch is a reliable predictor of learning in deaf children.

4. Discussion

4.1. Signers' gestures are comparable to speakers' gestures on math problems

Perry and colleagues (1988) gave 9–10-year-old hearing children the same mathematical equivalence task used in this study, and found that the hearing children produced gestures on 73% of their explanations. The comparable figure for the deaf children in our study was 80%, suggesting that deaf children gesture at approximately the same rate as hearing children on this task.

Perry and colleagues (1988) classified the hearing children in their study as mismatchers if they produced three or more gesture-speech mismatches. Using this definition, they found that 13 of 37 (35%) hearing children were mismatchers. The comparable figure in our study was 17 of 40 (42%) deaf children, suggesting that deaf and hearing children produce mismatches at comparable rates on this task.

Finally, Perry and colleagues (1988) examined posttest success as a function of mismatch taken as a categorical variable and found that 62% of mismatchers succeeded on the posttest, compared to 25% of matchers. The comparable figures in our sample were 65% vs. 22%, suggesting that mismatch is as reliable an index of readiness-to-learn in deaf children as it is in hearing children.

[5] Note that the effect size is an estimate of how likely it is that a given participant in the population (not in our particular sample) will improve; as a result, the effect size is smaller than the effect we actually found in the data.

4.2. The implications of finding mismatch in signers

Our findings have both theoretical and practical importance. Our study shows that signers can, and frequently do, produce spontaneous gestures that highlight different information from the information conveyed in their signs. Moreover, these gesture-sign mismatches predict learning in signers, just as gesture-speech mismatches predict learning in speakers.

Paivio (1971) has argued that both visual and verbal codes for representing information are used to organize information into knowledge. In Paivio's view, visual and verbal are not defined by modality—information is considered verbal whether it is written text or oral speech, and visual whether it is a picture or a non-linguistic environmental sound. Our findings lend credence to this view, and suggest that (in Paivio's terms) sign language is processed as verbal information, gesture as visual. Moreover, our findings take the phenomenon one step further, and suggest that mismatch's ability to predict learning comes not from the juxtaposition of different information conveyed in distinct modalities (hand vs. mouth), but rather from the juxtaposition of different information conveyed in distinct representational formats (a mimetic, analog format underlying gesture, *visual* in Paivio's terms, vs. a discrete, segmented format underlying language, sign or speech, *verbal* in Paivio's terms).

Our findings make it clear that mismatch can predict learning whether the verbal information is conveyed in the manual (sign) or oral (speech) modality. However, our data leave open the possibility that the visual information must be conveyed in the manual modality. The manual modality may be privileged when it comes to expressing emergent or mimetic ideas, perhaps because our hands are an important vehicle for discovering properties of the world (Sommerville, Woodward, & Needham, 2005; Goldin-Meadow & Beilock, 2010).

Our findings also have implications for teaching deaf children. Manipulating gestures that hearing children *see* during math instruction can turn children who are not ready to learn into learners (Singer & Goldin-Meadow, 2005), as can manipulating gestures that hearing children *produce* prior to (Broaders, Cook, Mitchell & Goldin-Meadow, 2007) or during (Goldin-Meadow, Cook & Mitchell, 2009) math instruction. Deaf children have documented delays relative to hearing children in a variety of areas of mathematical reasoning (Kritzer, 2009; Nunes & Moreno, 2002)—counting (Nunes & Moreno, 1998), word problems

(Zevenbergen, Hyde & Power, 2001), fractions (Titus, 1995), arithmetic comparison problems (Kelly, Lang, Mousley & David, 2003)—perhaps because they have fewer opportunities for incidental learning (Nunes & Moreno, 1998) or learning the culturally-transmitted aspects of math knowledge (Zarfaty, Nunes & Bryant, 2004), or perhaps because gesture is likely to be left out of the interpreted message deaf children receive in math classrooms. Sign language interpreters may sit a distance from the board on which a math teacher writes, and they often look at the deaf child for whom they are interpreting rather than at the teacher. If interpreters do not have access to the teacher's gestures, the information conveyed in gesture, which has been shown to facilitate learning in hearing children (Singer & Goldin-Meadow, 2005), will not be available to the deaf learner.

Whatever the cause of the math delays found in deaf children, our findings are important not only in deepening our understanding of the conditions under which mismatch predicts learning, but also in laying the groundwork for using gesture as a tool to facilitate learning in deaf as well as hearing children.

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