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The Impact of Gesture and Prior Knowledge on Visual Attention During Math Instruction

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Abstract

Inclusion of gesture – meaningful movements of the hands – during mathematics instruction is beneficial for teaching naïve learners novel concepts, and it can affect a learner's allocation of visual attention. Yet, it is unknown how children with pre-existing knowledge of a math concept approach instruction that includes gesture. Here, we examine how children's prior knowledge and either the presence or absence of gesture during instruction drive patterns in visual attention during a lesson. We find that prior knowledge does determine visual attention patterns, independent of type of instruction (i.e. with or without gesture). These findings further our understanding of the attentional mechanisms of gesture and have implications for real-world classrooms, where levels of prior knowledge are often mixed.

Keywords: gesture; eye tracking; mathematical equivalence; visual attention

Introduction

Gestures, movements of the hands that represent information through their form and movement trajectory (McNeill, 1992), play a fundamental role in education. Teachers naturally employ gesture as a teaching tool in the classroom (Alibali et al., 2014; Flevares & Perry, 2001), and verbal instruction incorporating gesture facilitates learning above-and-beyond verbal instruction alone (e.g., Congdon et al., 2017; Singer & Goldin-Meadow, 2005; Valenzeno, Alibali, & Klatzy, 2003). In particular, much research has focused on the benefits of gesture for teaching children the concept of mathematical equivalence – that two sides of an equation are equal. When used to teach children how to solve problems like 3+4+5=__+5, instruction with gesture has both short-term (e.g., Goldin-Meadow, Cook, & Mitchell, 2009) and long-term benefits (e.g., Cook, Mitchell, & Goldin-Meadow, 2008), and encourages flexible, generalizable learning (Novack, Congdon, Hemani-Lopez, & Goldin-Meadow, 2014).

Although the behavioral benefits of gesture for learning have been well documented over the past several decades (see Goldin-Meadow, 2016), the mechanisms by which gesture facilitates learning are not fully understood. Recent work has investigated one possible mechanism: that gesture may help children learn by guiding visual attention to important instructional elements (Wakefield, Novack, Congdon, Franconeri, & Goldin-Meadow, in press). Wakefield and colleagues asked children who had no understanding of the concept of mathematical equivalence (i.e., they answered 0 questions correctly on a pretest) to watch instructional videos on an eye tracker in one of two conditions, speech alone or speech+gesture instruction.

Replicating previous behavioral results, children in the speech+gesture condition performed significantly better on a posttest than children in the speech alone condition. Eye tracking data revealed that gesture also affected visual attention patterns: if taught with gesture, children looked more to the problem, less to the instructor, and were better able to synchronize their visual attention with spoken instruction. Additionally, children who saw gesture spent a much greater proportion of time fixating on the gesture itself than in previous eye tracking studies, which have investigated how people process gesture during face-to-face communication, such as story-telling (e.g., Gullberg & Holmqvist, 2006; Gullberg & Kita, 2009). Interestingly, only one aspect of visual attention during instruction was found to predict behavioral learning outcomes: children who were better able to synchronize their visual attention with speech performed better at posttest, but this was only true for children in the speech+gesture condition; there was no relation between ability to follow along with spoken instruction and learning outcomes for children in the speech alone condition. Based on these results, Wakefield et al. argue that gesture may facilitate learning by helping children identify the referents of a teacher's spoken instruction. However, because the previous study included only naïve learners, it is unclear whether the effects of gesture on visual attention are specific to children seeking to understand a concept, or may be indicative of how all children attend differently when gesture is used during instruction. Prior eye-tracking work with adults has shown that having knowledge in a domain changes what features of a task are attended to, and increases attention to task-relevant features during active problem solving (Kim & Rehder, 2011). A meta-analysis suggests that adult experts have shorter fixations, more fixations to task relevant areas, and fewer fixations on task redundant areas as compared to novices (Gegenfurtner et al., 2011). Therefore, adults change their visual attention patterns based on their degree of pre-existing knowledge. Yet it is an open question (1) whether expertise influences attention the same way in young children, (2) how prior knowledge might interact with instruction type, and (3) whether expertise may influence attention in a learning context.

In the present study, we compare patterns of visual attention during math instruction in two populations: children who already know how to solve math equivalence problems and children who do not. This allows us to determine whether the differences in looking during instruction in the previous study were specific to naïve learners, or whether adding gesture to instruction would similarly affect looking patterns in children with prior knowledge. We can also consider whether these factors (prior knowledge and instruction type) work independently to drive visual attention patterns, or whether they interact.

We draw on the same data set used by Wakefield et al. (in press) and Novack, Wakefield, Congdon, Franconeri, and Goldin-Meadow, (2016), but also consider a sample of children with prior knowledge (those who correctly answered 5 or 6 pretest problems) in addition to the children included in the original study (those who correctly answered 0 out of 6 problems).

Methods

Participants

Data from 71 children between the ages of 8 and 10 were analyzed for the present study (M = 8.8 years, 28 females). Participants were recruited through a database maintained by the University of Chicago Department of Psychology, and tested individually in a quiet, laboratory setting. Based on a pretest assessing children's ability to solve mathematical equivalence problems (e.g., 3+4+5=__+5), 28 children were classified as 'knowers' – children who correctly answered 5 or 6 (of 6) pretest problems, and 43 were classified as 'non-knowers' – children who correctly answered 0 of 6 pretest problems.[1] Classification based on prior knowledge occurred after the experiment had been completed. Prior to coming in for the study, participants were randomly assigned to condition. Of children classified as knowers, 15 had been randomly assigned to the speech alone condition and 13 had been randomly assigned to the speech+gesture condition. Of the children classified as non-knowers, 19 had been randomly assigned to the speech alone condition and 24 had randomly been assigned to the speech+gesture condition. Consent was obtained from parents. Children gave assent and received a small prize and $10 for participating.

Materials

Pretest. Children completed a pretest prior to training that consisted of 6 missing addend equivalence problems (3 problems with the form a+b+=__+c; 3 problems with the form p+q+r=p+__). Children also completed a posttest of the same format. Only data collected during training are considered here, thus, posttest results will not be discussed.[2]

Eye Tracker. Eye tracking data were collected via corneal reflection using a Tobii 1750 eye tracker with a 17-inch monitor and a native sampling frequency is 50 Hz. Tobii software was used to perform a 5-point calibration procedure using standard animation blue dots. This step was followed by the collection and integration of gaze data with the presented instructional videos (described below) using Tobii Studio (Tobii Technology, Sweden). Data were extracted on the level of individual fixations as defined by the Tobii Studio software. After extraction, fixations were subsequently separated into 50 msec bins, functionally allowing for downsampling of the original 50 Hz file without sampling the middle of a saccade.

Instructional videos. Instructional videos (6 for the speech alone condition; 6 for the speech+gesture condition; 25 sec each) were created to teach children how to solve missing addend math problems (e.g., 5+6+3=__+3). Videos showed a woman standing on the left side of a problem, written in black marker on a white board. At the beginning of each video, the woman said, "Pay attention to how I solve this problem", and wrote the correct answer in the blank (e.g., writing 11 in the previous example). Next, she described how to solve the problem, explaining the idea of *equivalence*: "*I want to make one side equal to the other side. 5 plus 6 plus 3 is 14, and 11 plus 3 is 14*, so *one side is equal to the other side.*" During spoken instruction, the woman kept her gaze on the problem. In the speech+gesture videos, the woman accompanied her speech with a gesture strategy. When she said "*I want to make **one side**…*", she

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[1] An additional 17 children participated in the study, but were not included in analyses because they correctly answered between 1 and 4 pretest problems (n = 10) or did not have usable eye tracking data (n = 7).

[2] For analyses considering the relation between looking patterns and learning outcomes, see Wakefield et al. (in press).

simultaneously produced a V-point with her index and middle figure to the first two addends, then, as she said "…the ***other side***" she moved her hand across the problem, bringing her fingers together to point to the answer with her index finger, showing a 'grouping' strategy. She produced no gestures in the speech alone videos. Speech was identical across the two training conditions: the actress recorded a single audio track for each problem.

Procedure

Children completed a written pretest containing 6 missing addend math problems. Children's performance on this pretest was used to classify them as knowers (those who answered 5 or 6 problems correctly) and non-knowers (those who answered 0 problems correctly) after the study concluded. The experimenter then wrote children's answers on a white board and they explained their solutions.

Next, children were seated approximately 18 inches from an eye tracking monitor, and told they would watch instructional videos to help them understand the math problems they had just solved. After undergoing calibration, they watched the first of the 6 instructional videos (speech alone, or speech+gesture, depending on the assigned training condition). After each instructional video, children were asked to solve a new missing addend problem on a small, hand-held whiteboard, and were given feedback on whether or not their answer was correct (e.g., "that's right, 10 is the correct answer" or "no, actually 10 is the correct answer"). A new, 6-question paper-and pencil posttest was administered following the instructional session.

Results

In order to compare looking patterns of children from each of the two groups (knowers and non-knowers), only eye tracking data collected while children watched the *first* instructional video were analyzed. Restricting analyses to the first training video, presumably before much learning had occurred, ensured the cleanest possible comparison between those with prior knowledge and those without.[3] Additionally, children with prior knowledge were liable to become bored over the course of the training, but it was assumed that the initial video would be novel enough to be of interest to all children.

A multistep process was used to extract data and prepare it for analysis: (1) Areas of interest (AOIs) were generated for the instructor, problem, and gesture space (see Figure 1) using Tobii Studio. The problem space was further separated to consider attention to specific addends, as well as the two sides of the problem. The remaining spaces outside of these AOIs were collapsed into an "other" AOI.

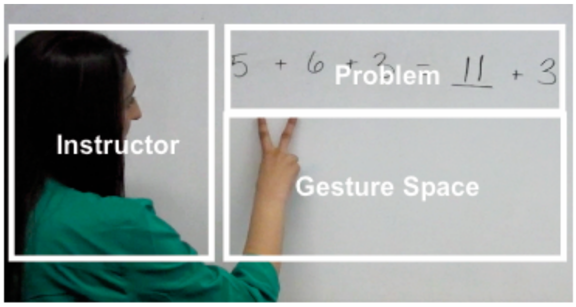

Figure 1. Still shot during a gesture strategy segment, with AOIs overlaid.

(2) Data were extracted and processed so that the AOI a participant fixated could be determined at 50 msec intervals across the entire length of each problem. (3) Time segments of interest during which a particular event was happening in the videos, were defined. Specifically, the **strategy segment** encompassed the two times when the instructor stated the equalizer strategy: *I want to make one side, equal to the other side.* During these segments, spoken instruction was identical across conditions, but children in the speech+gesture condition also saw co-speech instructional gestures. The **explanation segment** encompassed time when the instructor elaborated on the strategy, highlighting the particular addends in the problems (e.g., "*5 plus 6 plus 3 is 14, and 11 plus 3 is 14*"). This segment was identical across the experimental groups. (4) For each child, both following scores (how well the child fixated on elements mentioned in speech) and proportion of gaze in each AOI were calculated separately for each time segment. For gaze duration, the total gaze duration in each AOI (e.g., 1000 msec) was divided by total gaze duration for all AOIs during the segment to create a proportion of time spent in each AOI. To calculate following scores[4], we considered whether children's visual attention mapped onto referents as they were mentioned in speech. During the strategy segment, when the instructor stated the equalizer strategy "*I want to make* ***one side*** *equal to the* ***other side,***" following was defined as visually attending to one side of the problem when the instructor said "one side" and switching attention to the other side of the problem when the instructor said "other side". Children received a '1' if they looked from one side of the problem to the other during each of the two instances the equalizer strategy was spoken, a '0.5' if they looked from one side to the other during *one* of the instances, and a '0' if they did not look between the two sides of the problem during either presentation of the equalizer strategy. To calculate following during explanation segment, when the instructor explained the problem, *"**5** plus **6** plus **3** equals 14, and **11**, plus **3**, equals 14,"* following was defined as visually attending to each addend in the problem as it was mentioned in speech. Children received a score between 0 and 1 based on the proportion of addends they correctly attended to. For

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[3] Here, only eye tracking measures from the first instructional video was analyzed, whereas in Novack et al. (2016) all problems were considered, and in Wakefield et al. (in press) problems before a child's learning moment - the point at which the child began answering problems correctly and continued to answer correctly on subsequent problems – were considered.

[4] For more details about calculation of following scores, see Wakefield et al. (in press).

example, a child who attended to three of the 5 addends as they were mentioned in speech received a following score of 0.6 for the explanation segment.

Allocation of visual attention

Fixation during strategy segment. Figure 2 shows the proportion of time children spent looking to the instructor, problem, gesture space, and 'other' space during the strategy segment collapsed by knower status (Figure 2A) and condition (Figure 2B). Collapsing across condition, children categorized as non-knowers spent a greater proportion of time looking to the *problem space* as compared to children categorized as knowers (63% versus 50%) (*β*=0.13, *SE*=0.04, *t*=3.11, *p*<.05). In contrast, non-knowers allocated significantly less visual attention to the *instructor* than knowers (25% versus 39%) (*β*=0.14, *SE*=0.04, *t*=3.89, *p*<.001). Finally, there was no significant difference between the two groups in their proportion of time looking to either the *gesture space* (18% versus 18%) (*β*=0.00, *SE*=0.04, *t*=0.13, *p*=.90)[5] or the space classified as '*other'* (2% versus 1%) (*β*=0.01, *SE*=0.01, *t*=0.44, *p*=.90). The fact that both groups rarely allocated attention to space classified as 'other' suggests that children were equally attentive to relevant instructional elements overall, but divided their attention differently among these elements, based on prior knowledge.

Collapsing across knower-status, differences in fixation to the AOIs were also found when comparing children who received speech+gesture training and speech alone training. On average, children in the speech+gesture condition spent a greater proportion of time looking to the *problem* space (63% versus 49%) (*β*=0.13, *SE*=0.04, *t*=3.25, *p*<.05) and looking to the *gesture space* (18% versus 1%) (*β*=0.17, *SE*=0.02, *t*=7.81, *p*<.001) than children in the speech alone condition. In contrast, children in the speech+gesture condition allocated significantly less visual attention to the *instructor* than children in the speech alone condition (18% versus 48%) (*β*=0.30, *SE*=0.04, *t*=8.50, *p*<.001). Finally, children did not differ in the time looking to '*other'* by condition (1% versus 2%) (*β*=0.00, *SE*=0.01, *t*=0.04, *p*=.97).

There were no significant interactions between knower-status and condition for attention to any AOIs (*p*s >.39); but, this could have been due to a lack of power, given the relatively small knower group sample. To explore this possibility, additional analyses were conducted among just the knower group. All significant patterns seen at the whole group level were also seen when considering condition differences in *just* the knower group.

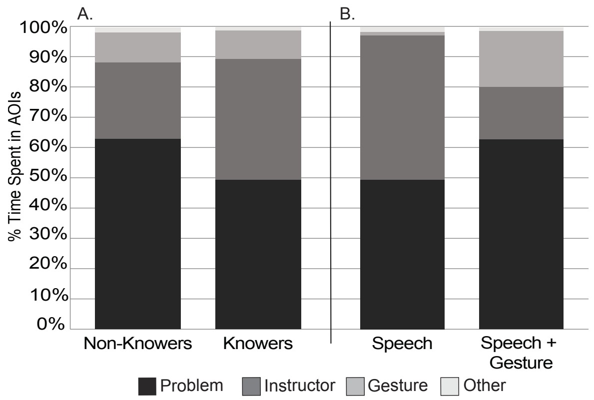

Figure 2. Fixation to AOIs during strategy segment by (a) knower-status and (b) condition.

Fixation during explanation segment. Figure 3 shows the proportion of time children spent looking to the instructor, problem, gesture space, and 'other' space during the explanation segment collapsed by knower status (Figure 3A) and condition (Figure 3B). Similar to looking patterns during the strategy segment, collapsed across condition, children categorized as non-knowers spent a greater proportion of their time looking to the *problem space* than children categorized as knowers (70% versus 59%) (*β*=0.10, *SE*=0.05, *t*=2.00, *p*<.05) and allocated marginally less visual attention to the *instructor* than knowers (28% versus 37%) (*β*=0.09, *SE*=0.05, *t*=1.82, *p*=.07). As gesture was not used during the explanation segment, it is unsurprising that children allocated very little attention to this AOI (<1% versus 2%) (*β*=0.01, *SE*=0.01, *t*=1.44, *p*=.15). Children also spent very little time visually focused outside of the instructional elements in the 'other' AOI, (1% versus 2%) (β=0.00, *SE*=0.02, *t*=0.15, *p*=.88), suggesting that they were paying attention to the content in the instructional video.

Collapsing across knower status, proportion of looking to each AOI did not differ by condition during the explanation segment. Additionally, there were no significant interactions between knower-status and condition for attention to any AOIs (*p*s >.20). As in strategy segment fixation analyses, additional analyses revealed that the patterns seen at the whole group level were also seen when considering condition effects in *just* the knower group.

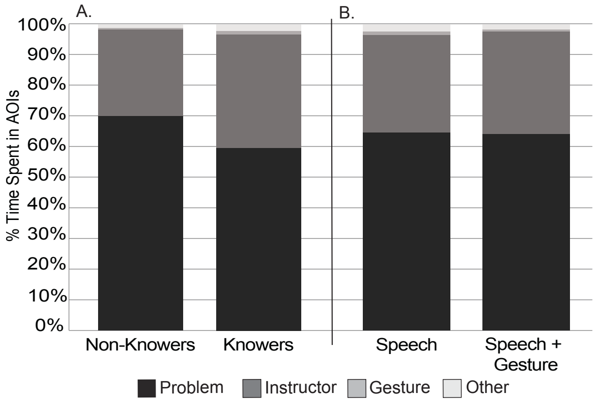

Figure 3. Fixation to AOIs during explanation segment by (a) knower-status and (b) condition.

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[5] In this comparison, only children in the speech+gesture condition were considered, as children in the speech alone condition would have no reason to look to the *gesture space*.

Following along with Speech

Following during strategy segment. Figure 4 shows children's ability to follow along with spoken instruction during the strategy segment, collapsed by knower status (Figure 4a) and condition (Figure 4b). Collapsing across condition, children categorized as non-knowers (*M* = 0.80, *SD* = 0.22) were more likely to following along with verbal instruction than children categorized as knowers (*M* = 0.63, *SD = 0.29*) (β=0.15, *SE*=0.06, *t*=2.72, *p*<.05). Collapsing across knower-status, children in the speech+gesture condition were more likely to successfully follow along with verbal instruction (*M* = 0.83, *SD* = 0.23) than children in the speech alone condition (*M* = 0.63, *SD* = 0.25) (β=0.19, *SE*=0.05, *t*=3.41, *p*<.05). The interaction between knower status and condition did not reach significance (β=0.01, *SE*=0.11, *t*=0.07, *p*=0.95). And again, additional analyses revealed that the patterns seen at the whole group level were also seen when considering condition effects in *just* the knower group.

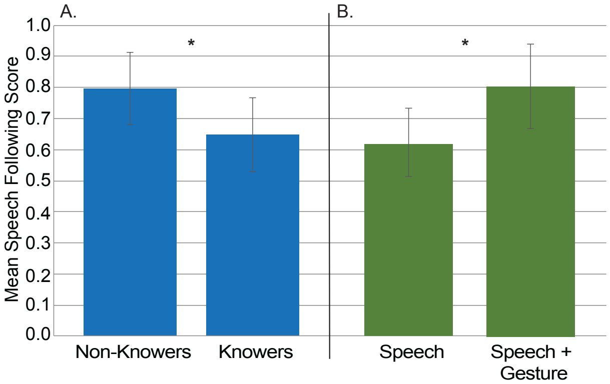

Figure 4. Following scores during the strategy segment by (a) knower-status and (b) condition.

Following during explanation segment. There were no differences between non-knowers and knowers, or those children in the speech+gesture or speech alone conditions, in regards to ability to follow along with verbal instruction.

Discussion

Prior work indicates that seeing gesture during math equivalence instruction influences how students allocate their visual attention (Wakefield et al., in press). In the present study, we asked whether these effects were driven, in part, by the children themselves. That is, we considered whether the impact of gesture on visual attention might differ based on children's prior knowledge of the domain of mathematical equivalence. Our results suggest that a child's prior knowledge state *does* impact his or her allocation of visual attention during instruction, but that these effects are independent from the effect of training condition. We found that children with prior knowledge spent less time looking to the problem and more time looking to the instructor, and were also less likely to follow along with speech, compared to children with no prior knowledge. Additionally, we found independent effects of condition, as expected based on similar analyses (Novack et al., 2016; Wakefield et al., in press). Specifically, children who saw instruction with gesture were more likely to look at the problem, less likely to look at the instructor, and more likely to follow along with speech, compared to children in the speech alone condition. Below, we consider the implications of these findings.

Fixation to instructional elements

During both the strategy and explanation segments, children without prior knowledge of mathematical equivalence looked less to the instructor and more to the problem than children who knew how to solve the problem. The presence of gesture also drove children to look towards the problem, irrespective of prior knowledge group. These results suggest that children play an active role in how they focus visual attention during instruction, based on what they need to gain from instruction: children who already knew how to solve these problems may have been more interested in how the instructor explained the problem, and not needed to refer to the problem directly, because they were already familiar with its form. In contrast, children who did not yet know how to solve the problems, and were therefore actively learning, were more likely to focus on problem, which would likely be more useful than the instructor's face.

These results can also be considered in relation to prior adult work, that suggests individuals with knowledge in a domain are more likely to focus on task-relevant features than novices (Gegenfurtner et al., 2011; Kim & Rehder, 2011). In contrast, our results show that knowers (our version of 'experts') looked *less* to the task-relevant features (i.e., the problem). However, it should be noted that our study differs from the previous work in that prior work considered experts versus novices while *solving* problems, rather than attending to instruction. Therefore, the differences might be indicative of the context in which eye tracking occurred, a question that should be addressed with future research.

Interestingly, we found that non-knowers and knowers in the gesture condition allocated the same amount of visual attention (18%) to the gesture space when gesture was present during the strategy segment. This diverges from research on how adults attend to gesture in communicative contexts. Prior work has found that adults rarely fixate on an interlocutor's gestures (<5%), spending much of their time focused on an interlocutor's face (e.g., Gullberg & Kita, 2009; Gullberg & Homqvist, 2006). Our findings suggest that children in the current study focused their attention much more on gesture than in previous narrative work precisely because of the context in which gesture was used – gesture was presented 'front-and-center' to children. This eliminates the alternative possibility raised by Wakefield et al., that the increased attention to gesture itself was due to naïve learners choosing to allocate attention on the gesture to help them gain an understanding of mathematical equivalence.

Ability to follow along with spoken instruction

Similar to fixation duration results, both prior knowledge of mathematical equivalence and training condition affect children's ability to follow along with instruction. Both children without prior knowledge (across both conditions) and those learning from gesture (across knowledge-states) follow along better with spoken instruction during the strategy segment. Why might that be?

First, the presence of gesture boosted children's likelihood to follow along with instruction. This may be because regardless of whether a child *needs* to gain an understanding of how to solve the problem on the board, the presence of a gesture, has a profound ability to direct visual attention.

Second, we report a novel finding: that prior knowledge also affects how well children attend to the referents of the instructor's speech – children with less prior knowledge are *more* likely to follow along, suggesting that they are taking an active role in their learning. Children who already know how to solve these problems may find it less important to closely link the instructor's speech to referents within the problem.

Through this work, we have established that not only does gesture use by an instructor affect visual attention during math equivalence learning, but visual attention patterns are also influenced independently by degree of pre-existing knowledge on a topic. This work allows us to further understand how children's individual differences may play a role in the classroom and influence what they glean from instruction. This work, and future work in this field, can begin to inform practical instructional techniques by helping educators design instruction that reaches diverse classrooms of learners.

Acknowledgments

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