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Students learn more when their teacher has learned to gesture effectively

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Teachers' gestures are an integral part of their instructional communication. In this study, we provided a teacher with a tutorial about ways to use gesture in connecting ideas in mathematics instruction, and we asked the teacher to teach sample lessons about slope and intercept before and after this tutorial. In response to the tutorial, the teacher enhanced his communication about links between ideas by increasing the frequency with which he expressed linked ideas multi-modally (i.e., using both speech and gesture), and by increasing the frequency with which he used simultaneous gestures to linked ideas. We then presented videos of a lesson the teacher provided before the tutorial (the *baseline* lesson) and one he provided after the tutorial (the *enhanced-gesture* lesson) to 42 seventh-grade students and assessed their learning. Students who received the enhanced-gesture lesson displayed greater learning about y-intercept than did students who received the baseline lesson. Thus, students learned more when their teacher had learned to gesture effectively.

Keywords: gesture, instruction, teaching, mathematics learning, algebra

Introduction

Teachers' gestures are an integral part of their instructional communication. Research on how teachers use gestures in naturalistic instruction is burgeoning (e.g., Alibali & Nathan, 2007; Alibali, Nathan, & Fujimori, 2011; Rasmussen, Stephan, & Allen, 2004; Richland, Zur, & Holyoak, 2007), and many studies have shown that teachers routinely produce gestures during classroom instruction. For

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example, Flevares and Perry (2001) studied three first-grade mathematics teachers' instruction about place value, and found that, on average, the teachers expressed mathematical information in gestures approximately 2.5 times per minute. Moreover, for each of the teachers, gesture was the most frequent nonverbal means of communicating mathematical information — more common than pictures, objects or writing.

Teachers' gestures are of particular interest in light of experimental evidence indicating that gestures matter for communication. A recent meta-analysis that included 63 studies yielded strong evidence that gestures are beneficial for language comprehension (Hostetter, 2011). Moreover, this meta-analysis revealed that the beneficial effects of gesture tended to be greater for children than for adults. These findings suggest that teachers' gestures might contribute in important ways to students' understanding of instructional material.

In line with these findings, several studies of gesture in instructional communication have shown that lessons with gestures promote deeper learning on the part of students than lessons without gestures (e.g., Cook, Duffy, & Fenn, 2013; Ping & Goldin-Meadow, 2008; Singer & Goldin-Meadow, 2005). For example, in one study, children learning about the concept of symmetry succeeded on more than twice as many posttest items (2.08 vs. 0.85, out of 6) if they received a lesson with gestures than if they received a lesson without gestures (Valenzeno, Alibali, & Klatzky, 2003). In another study, first-grade students learning about Piagetian conservation from videotaped lessons displayed deeper learning (i.e., were more likely to add new correct judgments for the tasks) if they received a lesson with gestures than if they received a lesson without gestures (Church, Ayman-Nolley, & Mahootian, 2004). For native English speakers, 91% showed deep learning from a speech-plus-gesture lesson, compared to 53% from the speech-only lesson; for Spanish speakers with limited English proficiency, 50% showed deep learning from the speech-plus-gesture lesson, compared to 20% from the speech-only lesson.

Other evidence suggests that teachers spontaneously adjust their gestures during classroom instruction in ways that may promote students' comprehension and learning. A recent study of "trouble spots" in middle school mathematics instruction revealed that teachers increased their gesture rates when their students displayed difficulty understanding the instructional material (e.g., by asking questions or providing incorrect responses to the teacher's questions). Teachers gestured at a higher rate in turns they produced after students demonstrated lack of understanding, compared to turns prior to students' misunderstandings (Alibali et al., 2013). These findings complement other research showing that students are more likely to take up information that teachers express in turns with gestures than information they express in turns without gestures (Goldin-Meadow, Kim, & Singer, 1999).

Taken together, these lines of work suggest that teachers' gestures are a powerful tool for supporting students' learning. Therefore, teachers' gestures warrant attention in an effort to understand instructional communication.

In this research, our focus is on teachers' use of gestures to link related ideas during mathematics instruction. Many forms of mathematics instruction involve making connections among mathematical ideas, such as lessons that focus on worked examples (e.g., Sweller & Cooper, 1985), lessons that involve analogies (e.g., Richland, Holyoak, & Stigler, 2004; Richland et al., 2007), and lessons that focus on contrasting related concepts (e.g., Hattikudur & Alibali, 2010) or contrasting multiple procedures for solving problems (e.g., Rittle-Johnson & Star, 2007). Teachers spontaneously use gestures when making connections in mathematics instruction, and they often produce gestures that link corresponding aspects of related representations (e.g., the y-intercept in a linear equation and the corresponding y-intercept on a graph of that equation) (Nathan & Alibali, 2011).

Indeed, a recent naturalistic study of 18 middle-school mathematics lessons (drawn from six different teachers) revealed that, in the large majority of cases when teachers sought to link ideas, they expressed one or both of those ideas multi-modally, typically in gesture and speech (and, in some cases, other modalities such as drawing or writing) (Alibali et al., 2014). These findings align with those of other researchers who have also argued that gestures are integral in instructional communication. For example, Flevares and Perry (2001) reported that, when teachers communicated about multiple mathematical representations, their communication almost always included gestures.

In the present work, we sought to create an intervention that could aid teachers in enhancing their use of gesture during instruction, and to measure the effects of this intervention on students' learning. Our investigation proceeded in two phases. In the first phase, we provided a teacher with a tutorial about ways to use gesture in connecting ideas in mathematics instruction, and we asked the teacher to teach sample lessons before and after this tutorial. Based on past research (Hostetter, Bieda, Alibali, Nathan, & Knuth, 2006), we expected that the tutorial would encourage the teacher to use both speech and gesture when expressing links between mathematical ideas. In the second phase of our investigation, we compared student learning from videotapes of a lesson the teacher provided before the tutorial (the *baseline* lesson) and one he provided after the tutorial (the *enhanced-gesture* lesson). Based on past research about the role of gesture in communication (reviewed in Hostetter, 2011), we predicted that students would learn more about connections among ideas if the teacher consistently expressed the linked ideas in both speech and gesture. Hence, we expected to see greater learning gains in the enhanced-gesture lesson.

When connecting ideas, teachers sometimes gesture about those ideas *sequentially* (e.g., first pointing to one representation of a mathematical idea and then to another), and at other times they gesture about those ideas *simultaneously* (e.g., pointing to one representation of a mathematical idea with the left hand and one with the right). Some research indicates that, when related ideas are presented simultaneously, learners better grasp the relationships between them (Christie & Gentner, 2010). Therefore, in the tutorial, we also encouraged the teacher to gesture to linked ideas simultaneously. We predicted that students would learn more if the teacher frequently linked ideas by gesturing simultaneously, than if he did so by gesturing sequentially.

Importantly, this study is the first to test the effects of variations in teachers' gestures on students' learning using a manipulation that was delivered to the *teacher*, rather than a manipulation provided directly to the students. In past studies examining the effects of teachers' gestures on students' learning, the manipulations of teachers' gestures were implemented either by scripting variations in an experimenter's speech and gesture (e.g., Perry, Berch, & Singleton, 1995; Ping & Goldin-Meadow, 2008) or by using videos that were scripted and filmed (i.e., with actors) so that the instructor's gestures varied (e.g., Church et al., 2004; Cook et al., 2013). In this study, in contrast, we encouraged a real teacher (not an actor or a member of our research team) to alter his gestures, and we examined whether this led to (a) changes in his gestural behavior, and (b) greater gains in students' learning. Thus, our manipulation was — quite literally — "in the hands" of the teacher.

In brief, this study breaks new ground by examining whether *teaching a teacher to gesture* in particular ways translates into better performance on the part of students. Relative to past experimental studies, this approach gives us less experimental control over the nature of the gestural input that the students receive, but it also has much greater ecological validity. Moreover, the teacher tutorial that we used is like a real-world teacher professional development experience in many ways. Therefore, if we find that teaching a teacher to gesture translates into greater student learning, it would have important practical implications.

In brief, in this study, we taught a teacher about how to use gesture when linking ideas in mathematics instruction, and we examined (a) whether this would lead to differences in the teacher's gestural behavior, and if so, (b) whether the enhanced-gesture lesson would lead to greater student learning than a baseline lesson.

Method

Phase 1: Constructing the video lessons

Teacher participants. To construct the video lessons that we ultimately showed to students in the main study, we recruited 4 preservice mathematics teachers. The teachers were asked to teach lessons about linear equations, focusing on the concepts of slope and intercept, to small groups of students, while being videotaped. We provided teachers with materials to use in the lessons, specifically, a set of story problems about a school band selling candy bars to raise money for a trip. The linear equations used in the problems were $y=2x$, $y=2x+15$, and $y=4x$. Teachers were asked to use equations and graphs in teaching the material.

Procedure. Each teacher was videotaped teaching the lesson four times. Each lesson was presented to a small group of 2–4 students. For the first two lessons for each teacher, teachers did not receive any instructions about gesture, so they gestured as they normally would, establishing for us a *baseline* of their gesture use. Between the second and third lessons, teachers received a brief tutorial about using gesture to link ideas. Following the tutorial, teachers taught the lesson twice more, to two new groups of students. We refer to these lessons as *enhanced-gesture* lessons.

The tutorial focused on different ways of making links between representations of mathematical ideas (e.g., links between an equation and the corresponding graph) using gestures. The tutorial included descriptions and demonstrations of several ways of visually displaying connections, including using sequential or simultaneous pointing gestures, and using sets of depictive gestures that use similar handshapes and motions. The full script of the tutorial is presented in Appendix A.

Selecting a pair of lessons to use in the study of student learning. For the study of student learning, we selected a pair of lessons from a single teacher — one lesson from the baseline condition and one from the enhanced-gesture condition. To select these lessons, we reviewed the four videos from each teacher, and selected a pair of lessons from a single teacher for which (1) content was largely similar across the two lessons, (2) video quality was good for both lessons. We excluded one teacher from consideration because much of her writing on the board was not visible in the video due to the combination of the lighting conditions and the particular marker colors that she chose to use on the whiteboard during her lessons. We excluded another teacher from further consideration because there were several no-shows on the part of students for her session, so two of her lessons were taught to only one or two individuals.

The pair of lessons that we ultimately selected was from a male teacher. We used this pair of lessons for the main study focusing on student learning (described below), and we also examined whether there were differences across lessons in the teacher's gesture production that aligned with the gestural practices that had been instructed in the tutorial. To foreshadow the results, the teacher did alter his gestures in the requested ways, providing an "existence proof" that speakers can in fact alter their gestures in response to a brief tutorial. We next describe how we coded the lesson videos, and following that, we describe the method for the study of student learning.

Coding the lesson videos: overview. We prepared a full verbal transcript for each of the teacher lessons in the target pair. We then coded the lessons in five steps, each of which is described in more detail below: (1) we identified and categorized the teacher's gestures, (2) we identified linking episodes within the lessons, (3) we coded the modalities in which the teacher expressed linked ideas in each linking episode, (4) for linking episodes in which the teacher expressed both linked ideas in gesture, we coded whether the link involved simultaneous or sequential gestures, and (5) we identified filled pauses (i.e., *um* and *uh*) and speech errors (e.g., repeated words, self-corrections) in the teacher's speech.

Coding the teacher's gestures. We segmented individual gestures from one another based on changes in handshape, placement or motion. Next, using a coding system adapted from the one presented by McNeill (1992), we classified each gesture into one of five categories: points, depictive gestures, tracing gestures, writing gestures, or beats. *Points* are gestures that involve extending a finger (usually the index finger) or the entire hand to indicate an object, a location, or an imaginary object or location in space (e.g., pointing with the right index finger to an equation on the whiteboard). *Depictive gestures* are gestures that depict their meaning either via handshape or motion trajectory. Such gestures usually depicted meanings literally (e.g., holding both hands up with the index fingers and thumbs extended to represent a candy bar) and sometimes depicted meanings metaphorically (e.g., flicking the wrist away from the head to represent "just knowing" a math fact). *Tracing* gestures are gestures that trace a path along an object or inscription (e.g., tracing an axis on a graph on the whiteboard). In addition to their iconic content, tracing gestures also incorporate aspects of deixis. *Writing gestures* are indexical writing actions that are aligned with speech in the same way that other gestures are. For example, at times the teacher underlined or circled items on the whiteboard while speaking; if these writing actions were aligned with speech, they were coded as *writing gestures* (e.g., saying "the green graph" while circling a portion of the green equation on the board). Finally, *beats* are rhythmic, up-and-down hand movements that are often aligned with the prosody of speech, and that have no clear semantic meaning.

To assess reliability in coding the teachers' gestures, we randomly selected a starting point in each of the two lesson transcripts, and identified a segment of approximately 500 words beginning at that point; these segments represent 16% of the total 6221 words in the two lessons. A second coder identified and classified gestures for these segments. Agreement between the original coder and the second coder for identifying gestures was 89% ($N = 185.5$),[1] and agreement for classifying gestures into categories was 85%, $\kappa = .81$ ($N = 166$, 19.6% of the total 845 observed gestures).

Identifying linking episodes. We reviewed the speech and gesture transcripts of the lessons and identified "linking episodes", which we defined as segments of discourse in which the teacher sought to link two (or in some cases, three or more) mathematical ideas or representations of mathematical ideas (see Alibali et al., 2014). We considered *mathematical representation* broadly, to include not only the common mathematical inscriptions used in the lessons (e.g., equations and graphs), but also verbal expressions of mathematical ideas and gestural depictions of mathematical ideas (e.g., a line drawn in the air with the index finger). For each linking episode, we identified the specific ideas or representations that were involved (e.g., equations, graphs, elements of the story problem, and so forth).

Linking episodes typically extended over multiple lines of the verbal transcript. Within each linking episode, we then identified the *target link*, defined as the specific portion of the linking episode in which the relationship between ideas or representations was expressed. For example, at one point the teacher connected the *y* in an equation with the *y*-axis of the graph, saying "*Y* is now the number of dollars" while pointing to the y in the equation and to the y-axis of the graph. Most target links were between one and four lines of transcript.

Coding the modalities in which the teacher expressed linked representations. Next, we identified the modalities that the teacher used when he expressed each of the linked ideas within each target link. In the lessons that we analyzed here, the modalities that the teacher used were speech, gestures, and writing.

To assess reliability, a second coder assessed modalities for each of the ideas in the linking episodes that occurred in the two 500-word segments that had been selected for reliability coding. Agreement between coders was 89% ($N = 36$ linked ideas, which represents 17% of the total of 213 linked ideas in the dataset), $\kappa = .80$.

Coding gestures within linking episodes as sequential or simultaneous. Finally, for each linking episode in which the teacher linked two or more ideas using gestures (with or without speech) we classified the gestures as either sequential or simultaneous. If the teacher's gestures to the linked ideas occurred one after the other, then the episode was classified as containing a *sequential* gestural link. For example, in one case, the teacher pointed to the equations while saying "I have three different equations", and then pointed to the graph while saying "and I got to map 'em up here". This episode was coded as containing a *sequential* gestural link. If the teacher's gestures occurred together in time, then the episode was classified as containing a *simultaneous* gestural link. For example, in one case, the teacher pointed to the *y* in an equation with his left index finger while saying "I'm going to take this" and then held that point while simultaneously tracing the *y*-axis of the graph with his right index finger and saying "find forty" (referring to a value on the *y*-axis); this episode was coded as containing a *simultaneous* gestural link. If any portion of the gestural linking was simultaneous, the link was coded as simultaneous; thus, if the teacher gestured first to one representation with one hand, and then held that gesture in place while gesturing to the other representation with the other hand, the gestural link was coded as simultaneous.

To assess reliability for coding gesture within linking episodes as sequential or simultaneous, we identified the linking episodes within the two 500-word reliability segments that included two or more linked ideas that were both expressed in gesture. For each of these episodes, the coder scored whether the gestures to the linked ideas were sequential or simultaneous. Agreement between coders was 100% ($N = 6$, which represents 11% of the 57 linking episodes that included two or more linked ideas expressed in gesture), $\kappa = 1.0$.

Coding filled pauses and speech repairs. We also coded two aspects of the teacher's verbal fluency. First, we identified all filled pauses (*um*s and *uh*s) in the transcripts. Second, we identified all speech errors (see Levelt, 1983), including repetitions (e.g., "and I, I have no idea how many candy bars we're going to sell"), repairs (e.g., "Two bucks a piece for a nice big old Snickel- Snickers bar"), fresh starts (e.g., "Alright so two dollars for — what about times five?"), and uncorrected syntactic errors (e.g., "So what you're gonna do, is they think about like this"). To assess reliability for coding speech errors, a second coder identified speech errors in the two 500-word reliability segments. Agreement between the reliability coder and the original coder for identifying speech errors in the stream of speech was 80% ($N = 17.5$).

Study of student learning

Student participants. Participants were 42 seventh-grade students (20 boys, 22 girls) recruited from a public school district in the Midwestern United States. The sample included 25 Caucasian participants, 6 Asian participants, 4 African-American participants, 1 Native American participant, 2 participants of Hispanic ethnicity, and 4 participants who reported more than one race or ethnicity. Students were invited to participate via letters that were sent home in their backpacks from their middle schools. Students were eligible to participate in the study if they were enrolled in the standard seventh-grade mathematics course.

Procedure. Students were randomly assigned to receive either the baseline videotaped lesson or the enhanced-gesture videotaped lesson. In this phase, data were collected in groups of 1–4 students.

Students completed an eight-item test of their knowledge about slope and intercept both before and after viewing their assigned lesson. Items on the pretest and posttest were isomorphic, but used different numbers and scenarios. On each item, students had the opportunity to represent slope and intercept in their responses. For example, students were asked to construct a graph to correspond with an equation or a story, and to write an equation to correspond with a graph or a story (see Appendix B for example items).

Coding students' pretest and posttest responses. Each of the students' responses was coded in terms of whether they correctly represented slope and intercept.

To assess reliability for coding students' pretest and posttest responses, a second coder recoded the data for 6 participants (14% of the dataset). Agreement between coders for classifying responses as correct or incorrect was 98% for slope ($\kappa = .96$) and 100% for intercept ($\kappa = 1.0$).

Results

Did the teacher alter the total number of links he expressed across the two lessons?

We were concerned that the gesture tutorial might highlight the importance of linking ideas in instruction in a general way, so we first sought to insure that it did not lead the teacher to express more links among ideas, overall. If the tutorial did promote linking more generally, any effects we observe on student learning might be due to the total *number* of linking episodes, rather than to the teachers' gestural behavior. To address this possibility, we examined the number of times the teacher linked ideas in the baseline and enhanced-gesture lessons. He produced 45 links in the baseline lesson, and 42 links in the enhanced-gesture lesson. Thus, there was little difference in the total number of links produced across lessons.

Did the teacher alter his gesture production in the enhanced-gesture lesson?

We next evaluated the teacher's gesture production in the two lessons, focusing on three dimensions of the teacher's behavior: (1) his gesture rate, (2) whether he expressed linked ideas multi-modally or in a single modality, and (3) whether he expressed gestural links simultaneously or sequentially.

Gesture rate. The teacher gestured at a higher rate in the enhanced-gesture lesson than in the baseline lesson (16.4 vs. 13.0 gestures per 100 words). To test this difference statistically, we divided each lesson into eight segments, and compared the teachers' gesture rate in the baseline and enhanced-gesture lessons across these eight segments, using a paired-samples Wilcoxon signed-ranks test. The difference in gesture rates was significant, $z = 2.45$, $p = .01$, two-tailed.

We next compared the teacher's gesture rates for each of the five gesture types separately (points, depictive gestures, tracing gestures, writing gestures, and beats), again using two-tailed paired-sample Wilcoxon signed ranks tests. The data are presented in Figure 1. The teacher produced significantly more depictive gestures and more tracing gestures in the enhanced-gesture lesson than in the baseline lesson (depictive gestures, $z = 2.03$, $p = 0.04$; traces, $z = 2.38$, $p = 0.02$). The teacher also produced more points in the enhanced-gesture lesson, but this difference was not significant ($z = 1.47$, $p = 0.14$). The teacher produced comparable numbers of beats ($z = 1.05$, $p = .29$) and writing gestures ($z = .42$, $p = .67$) in the two lessons.

Multi-modal vs. uni-modal expression of linked ideas. We next examined how the teacher expressed linked ideas in the two lessons. The teacher often expressed linked ideas multi-modally (i.e., in both speech and gesture), and in some cases he expressed linked ideas uni-modally (i.e., in speech alone or in gesture alone). We classified linking episodes as multi-modal if the teacher expressed *both* (or, for links that involved more than two ideas, *at least two*) of the ideas in the target link in both gesture and speech. The percentage of multi-modal linking episodes was greater in the enhanced-gesture condition than in the baseline condition (67% vs. 42% of target links), $\chi 2(1, N = 87) = 5.23$, $p < .02$.

Sequential vs. simultaneous gesture. Finally, for linking episodes in which the teacher used gesture in expressing both linked ideas, we examined the likelihood that the teacher used simultaneous gestures for both ideas. The teacher was much more likely to use simultaneous gestures to both ideas in the enhanced-gesture lesson than in the baseline lesson (76% vs. 4% of links that included gesture), $\chi 2(1, N = 57) = 26.52$, $p < .001$.

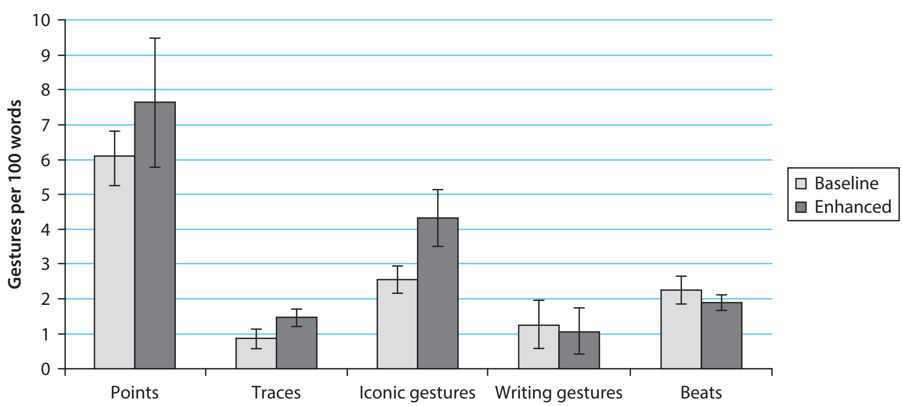

Figure 1. Mean rate of gestures of each per 100 words, across eight segments of the lesson, in the baseline and enhanced-gesture conditions

Summary. These data suggest that the teacher was responsive to the gesture-enhancement tutorial, altering the ways in which he used gestures to express links between ideas. He was more likely to express linked ideas multi-modally, more likely to use simultaneous gestures to link ideas, and more likely to use tracing gestures and depictive gestures. Importantly, however, he did not alter the overall frequency with which he expressed links between ideas across the two lessons. In brief, the teacher altered the *way* in which he communicated about links, but not the total number of links.

Did students learn more from the enhanced-gesture lesson?

Given that the teacher did alter his gesture production in the predicted ways, we were in a position to address our primary question: did students who received the enhanced-gesture lesson display greater learning than those who received the baseline lesson? Recall that students received a score for slope and a score for intercept at each test. Slope and intercept scores were strongly correlated ($r = .78$ at pretest); however, a substantial number of students scored near or at ceiling for one concept but not for the other. Therefore, we analyzed students' learning of slope and intercept separately, and for each analysis, we excluded students who scored 8 or 9 (of 9) points at pretest, as they did not have room to improve in their understanding of that concept.

The data are presented in Figure 2. For understanding of slope, pretest-to-posttest gains were comparable for students in the enhanced-gesture and baseline conditions ($M = 3.00$ vs. $M = 2.94$). However, for understanding of intercept, pretest-to-posttest gains were greater for students in the enhanced-gesture condition

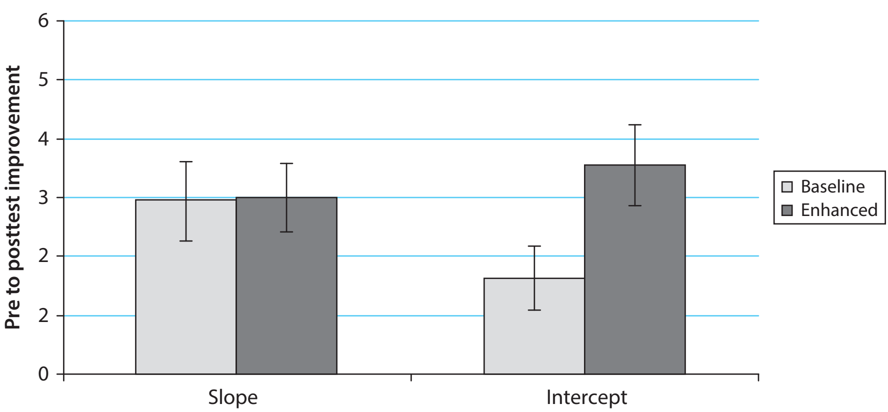

Figure 2. Pretest to posttest improvement on slope and intercept for students in the baseline and enhanced-gesture conditions

($M = 3.54$ points gained) than in the baseline condition ($M = 1.63$ points gained), $t(27) = 2.18$, $d = 2.97$, $p = .04$, two-tailed.

Could the observed differences be due to differences between conditions in the teacher's speech rate or fluency?

In light of the observed differences in student learning about intercept across conditions, we considered whether those differences might be due to aspects of the teacher's verbal behavior, such as the rate or fluency of his speech. If these aspects of the lessons did not differ, it would help make the case that the observed differences in learning about intercept are due to differences in the teacher's gestures, We considered three aspects of the teacher's verbal behavior: speech rate, rate of filled pauses (e.g., *um* and *uh*), and speech errors.

The teacher's behavior was highly similar across conditions on all three of these measures. First, the teacher's speech rate was almost identical in the baseline and enhanced-gesture conditions: 2.50 words vs. 2.51 words per second. Second, the rate with which the teacher produced filled pauses was also very similar across conditions: 0.17 per 100 words in the baseline condition, and 0.19 per 100 words in the enhanced-gesture condition. Finally, the rate at which the teacher produced speech errors was also highly similar across conditions: 1.04 per 100 words for the baseline condition and 1.00 per 100 words in the enhanced-gesture condition. Thus, there was no evidence to suggest that differences in the teacher's speech rate or fluency might be responsible for the observed differences in student learning about intercept.

Discussion

The present findings suggest that teachers' communication about links among ideas can affect students' learning from mathematics instruction. The teacher in this study increased the frequency with which he used tracing and depictive gestures, increased the frequency with which he expressed target links multi-modally, and increased the frequency with which he used simultaneous gestures to both ideas. These alterations in the teacher's gestural behavior were associated with greater gains in student learning about y-intercept. There were not corresponding differences in the total number of links, or in the teacher's speech rate or fluency. Taken together, these data suggest that teachers' gestural communication about links between ideas can affect how much students learn.

These findings are important, because they are the first direct evidence that intervening with teachers to enhance the effectiveness of their gestures can actually affect students' learning. In this study, the experimental manipulation was delivered to the *teacher*, and he then altered his communicative behavior in instructing students. Our findings are the first to show that helping a teacher to enhance his gestures can translate into better performance on the part of his students.

In both the baseline and enhanced-gesture lessons, the teacher produced primarily pointing and depictive gestures. The types of gestures that differed most across conditions were tracing gestures (which involve a combination of pointing and movement) and depictive gestures. How might such gestures foster learning? In past research, we have argued that *pointing* gestures serve to *ground* the accompanying speech in the physical environment, and in so doing, they may scaffold students' understanding of that speech (Alibali & Nathan, 2012). For example, if the teacher says "*y*-intercept" while pointing to the *y*-intercept, learners may more easily grasp the referent of the (potentially unfamiliar) mathematical term. Tracing gestures could serve this function as well. For example, if the teacher traces along the *x*-axis while saying "*x*-axis", learners may be more likely to successfully identify the referent of the term.

Depictive gestures, as their name implies, depict objects and actions using handshape or motion. Some researchers have argued that depictive gestures manifest speakers' mental simulations of actions or perceptual states (Hostetter & Alibali, 2008). Speakers' depictive gestures may also contribute to listeners' comprehension by guiding listeners' mental simulations of actions and perceptual states (Alibali & Hostetter, 2011). In this study, some of the teachers' depictive gestures may have helped students to mentally simulate aspects of the story scenario (e.g., depicting the candy bar that students were selling in the story problem). Other depictive gestures represented elements of the graphs (e.g., saying "they run parallel to each other" while moving both hands diagonally upwards with palms facing each other to depict the parallel lines on the graph), highlighting these elements, and perhaps making them more likely to be part of the students' mental simulations of the graphs.

In our tutorial, we encouraged the teacher to gesture specifically when he spoke about *connections* across multiple external representations of mathematical concepts, such as connections among graphical, symbolic, and verbal representations of slope and intercept. Our pre- and posttest were designed to assess students' grasp of the connections across representations. We suggest that the teachers' gestures may have helped learners to more accurately interpret the referents of the teacher's speech about the representations being linked, and to more effectively simulate those linked representations (e.g., to mentally simulate the story scenario).

The teacher in this study dramatically increased his use of *simultaneous* gestures from the baseline to the enhanced-gesture condition (from 4% to 76% of links that involved gesture to two or more linked ideas). In this regard, it seems likely that the beneficial effect we observed on student learning is due in large part to his increased use of simultaneous linking. In simultaneous linking gestures, connections are directly manifested via the speaker's body. We speculate that such gestures may help to reduce the cognitive demand inherent attending to and integrating across multiple ideas (see Mayer & Moreno, 2003, for discussion of this general issue).

Of course, some limitations to this study must be acknowledged. First, our findings are based on a single teacher, a single age group and lesson topic, and a single pair of lessons. Further research with other teachers, grade levels, and math concepts is needed in order to establish the generality of our findings.

Second, we found beneficial effects of the teacher's enhanced gestures on students' understanding of intercept, but not slope. Why might this be the case? Overall, students learned less about intercept than about slope, which aligns with other reports in the literature suggesting that intercept is a more challenging concept for young learners than slope (Hattikudur, Prather, Asquith, Alibali, & Knuth, 2012). In this study, students demonstrated gains in slope understanding regardless of the teachers' gestures. In contrast, for intercept, students gained little in the baseline condition, but showed substantial gains in the enhanced-gesture condition. It may be that gestures are most important for concepts that are more challenging for students. This view is compatible with other research suggesting that gesture matters more for comprehension for complex utterances than for simple ones (McNeil, Alibali, & Evans, 2000).

Despite these limitations, our main findings are clear: The teacher in our study did alter his gestures in response to a brief tutorial about gestural linking, and students who viewed the enhanced-gesture lesson learned more than students who viewed the baseline lesson. These findings suggest that there is likely to be value in teaching teachers about effective ways to communicate multi-modally about links between ideas. Our work suggests that teachers can adopt pedagogically effective gesturing, and that if they do so, it may offer benefits to their students.

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Note

1. To assess reliability in identifying gestures from the stream of manual behavior, we use the formula *N* (gestures seen by both coders) / [*N* (gestures seen by both coders) + 0.5**N* (gestures seen by one coder)]. Gestures seen by only one coder are weighted by 0.5 in the denominator, because they could be either gestures that one coder missed *or* non-gestural movements that are incorrectly attributed to be gestures.

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Appendix A

As I'm sure you've noticed during the lessons so far, that there is a strong focus in this lesson on showing how an equation is related to a real-life situation, as reflected in the story, and how it is related to a visual image like a graph. That is, what is happening in the story can be connected to the equation, and both of those can be connected to the graph. Also, the slope and y-intercept in the graph can be connected to the slope and y-intercept in the equation.

One thing that might really help students connect the equation, the story and the graph is to use gesture. You may not have noticed, but you probably use gestures to help students visualize mathematical relationships when you teach in class. You have probably also been using gestures in the lessons you've already given today. In the remainder of the tutorials that you give today, we would like you to really increase your use of gesture to help students understand connections.

There are a number of different ways you might highlight connections through your gestures. For instance, you might point to both of the ideas being connected at the same time or in close succession. For example, to connect the idea of the intercept in the new graph to the intercept in the equation, you might point to the y-intercept at 15 on the graph with one hand while you point to the "+15" in the equation with the other hand. (*Demonstrate simultaneous pointing gesture*.)

Or, to connect the words "amount of money" in the story with the *y* in the equation, you might point to the word "amount" with one hand while pointing to the y in the equation with the other hand. (*Demonstrate simultaneous pointing gesture.*) Or, to connect the y in the equation with the y-axis of the graph, you might point to the y-axis with one hand and to the y in the equation with the other hand. (*Demonstrate simultaneous pointing gesture.*)

You might also connect ideas by using gestures that have a similar form or motion. For example, you might use gesture to show how the parent's donation is increasing the total amount of money the students have (*demonstrate depictive gesture with palm down that moves vertically upward*) and therefore the intercept in the graph is also increasing (*demonstrate a depictive + deictic gesture where same hand shape — palm down — starts at 0 and then moves up the y-axis to 15 on the graph*). Similarly, for the idea of slope, you might produce one gesture that shows the original slope of the line changing to be steeper when the candy bars cost twice as much and a similar gesture overlaid on the graph to emphasize the same concept (*demonstrate depictive gesture with left arm flat diagonally across body, fingers pointing towards 2 o'clock, then rotating elbow up so that fingers point towards 1 o'clock; then move gesture so that it is overlaid on the slope of the graph, and again rotate up/out so it is in line with the new slope*).

For the remaining two lessons today, please try to use as many gestures as possible that clearly show connections between the story and the graph, the story and the equation, and the equation and the graph. I'm sure you have already been using some gestures in your lessons; for these remaining lessons, just try to boost your overall number of gestures and try to use them as much as possible to show connections between ideas. Do you have any questions?

Appendix B

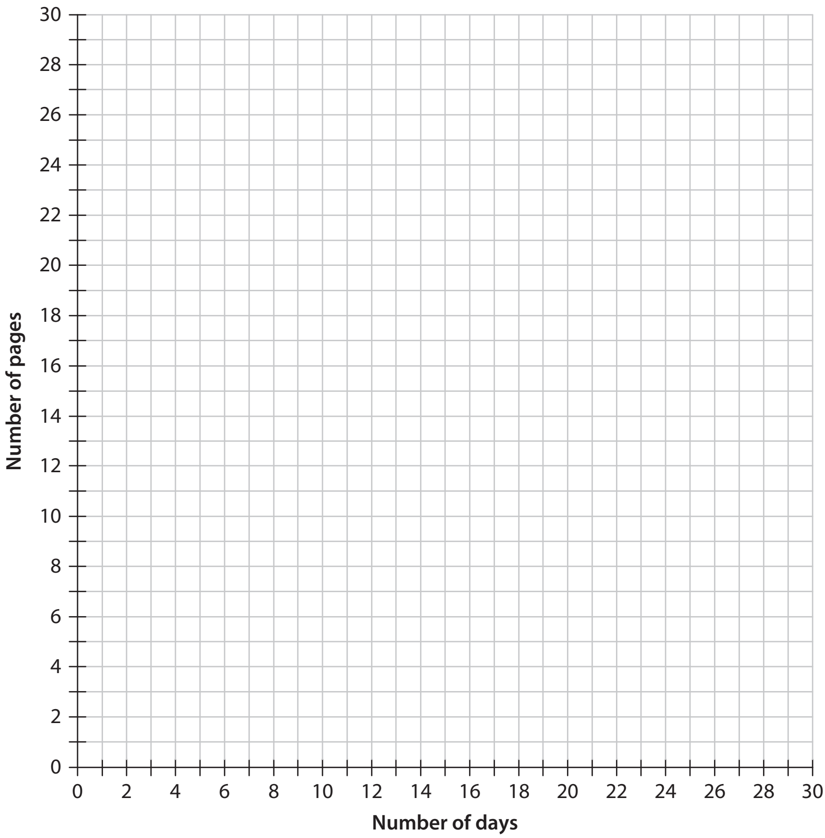
Kristen and Chelsea are writing a story together. Chelsea wrote the first 7 pages. Kristen is going to write the rest of the story. She writes 3 pages per day.

This story can be represented with the following equation:

$$y = 3x + 7$$

where y = the total number of pages
x = the number of days that Kristen has written

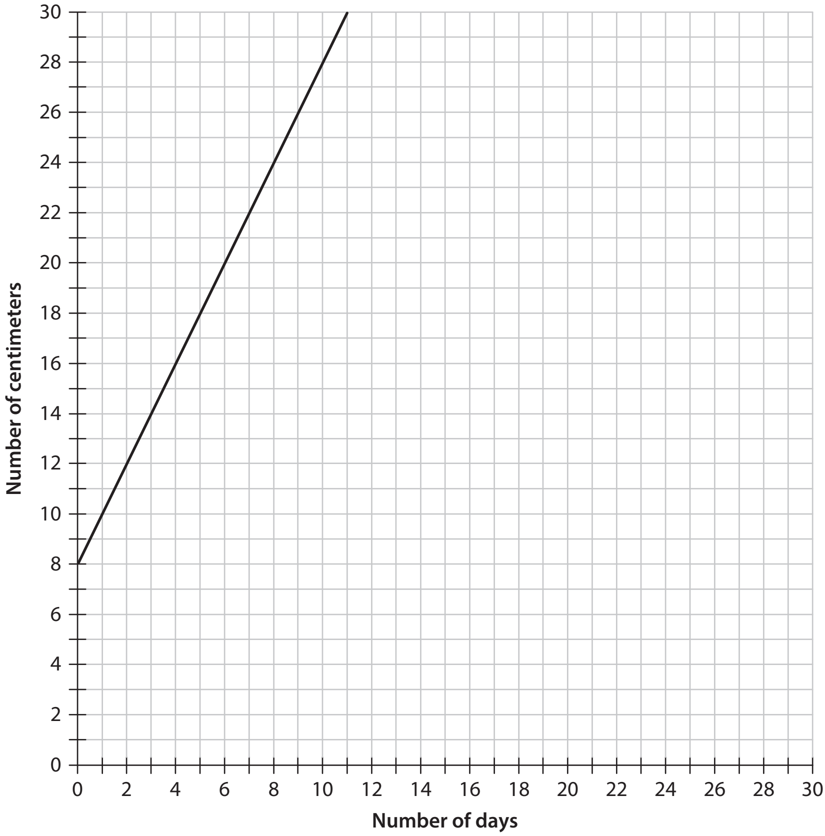
Draw a graph to represent this situation.



Travis bought a small tomato plant at the garden store and planted it in his garden. It was 8 centimeters tall on the day he bought and planted it.

The graph below shows the growth of the plant, starting from when Travis planted it.

Write an equation that represents the growth of Travis's plant.

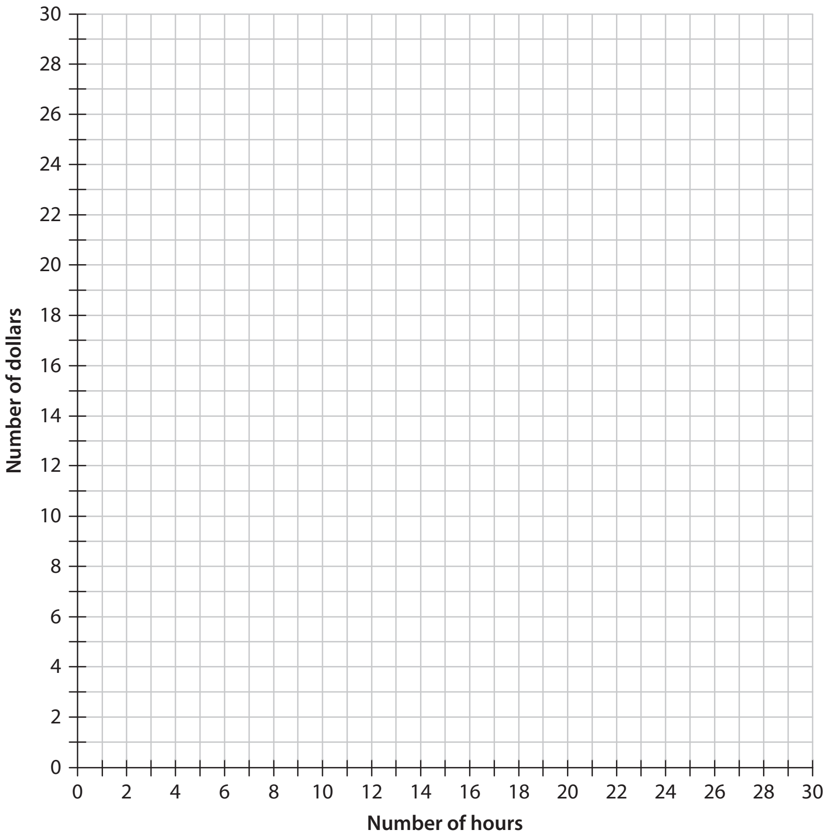


Amy has a new kitten, Wilcox. At birth, Wilcox weighed 6 ounces. Each day he gains 1 ounce.

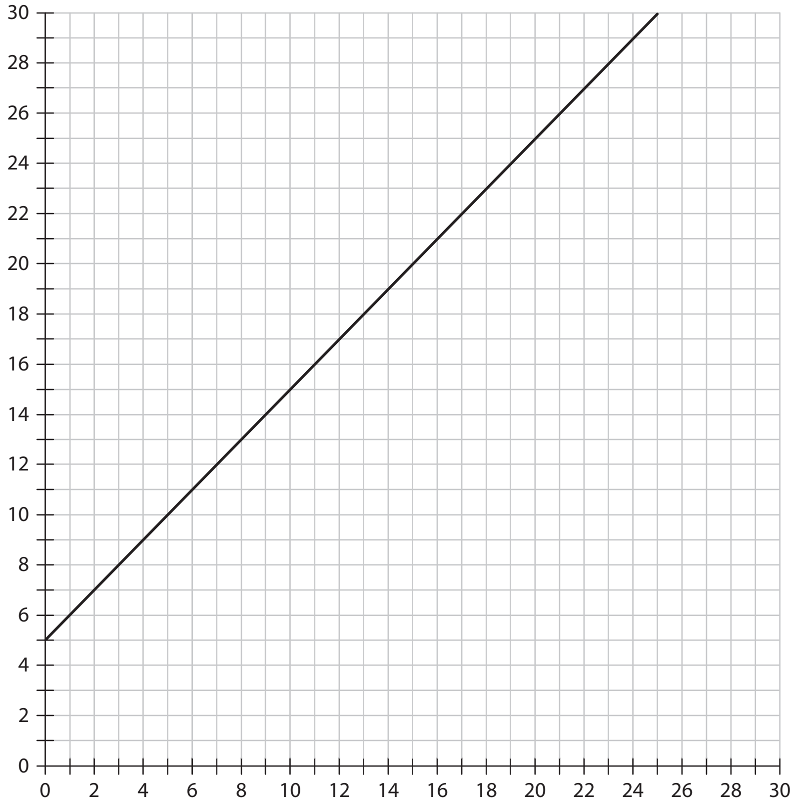
Write an equation that represents this situation. Let y = Wilcox's weight in ounces, and let x = the number of days since Wilcox was born.

Rebecca is saving to buy a bicycle. She starts out with $6 in her savings account, and she earns $3 for each hour that she babysits. She can save all of her babysitting money.

Draw a graph that represents this situation.



Write an equation for the line in the graph below.



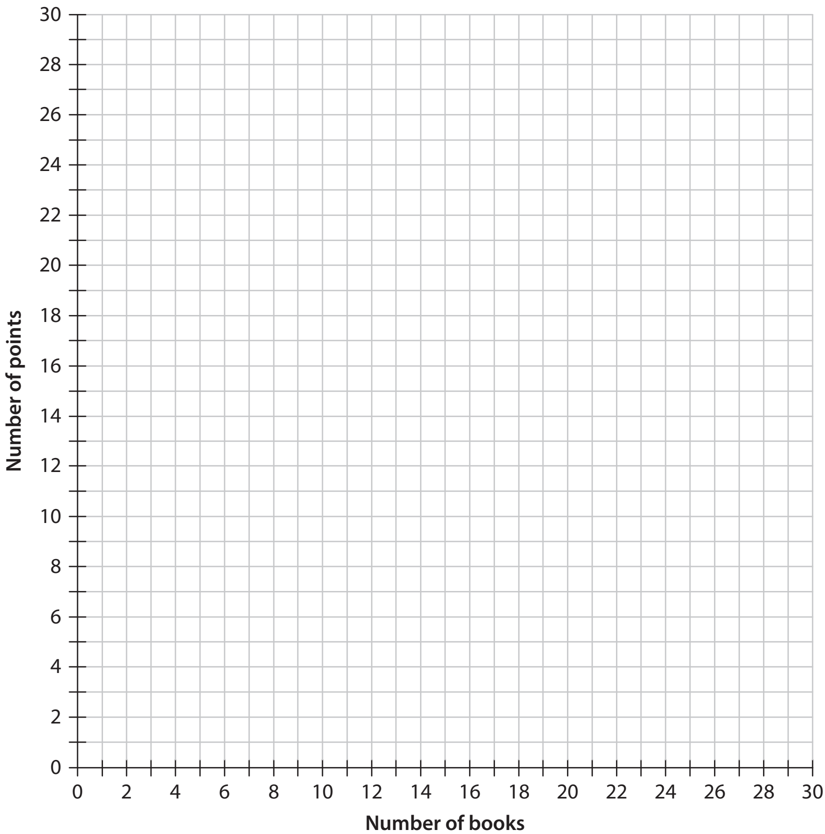
Max is in a summer reading program at the public library. Students in the program get 2 points for each book they read. At the end of the summer, they receive prizes based on the number of points they have earned. At the beginning of the program, Max gets 5 points as a bonus for getting a library card.

This story can be represented with the following equation:

$$y = 2x + 5$$

where y = the total number of points
x = the number of books Max has read

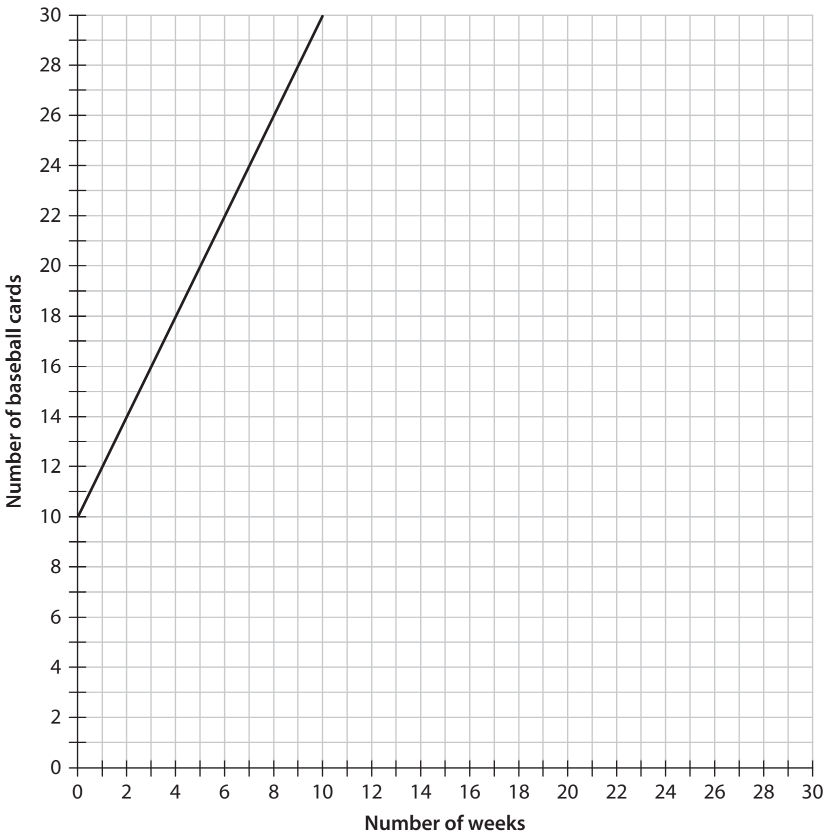
Draw a graph to represent this situation.



Jack is collecting baseball cards. His aunt gave him 10 special cards to get his collection started. He uses his allowance to buy new cards each week.

The graph below shows the size of Jack's baseball card collection, starting from when he received the gift of 10 cards from his aunt.

Write an equation that represents the change in size of Jack's collection.



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