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Proceedings of the Annual Meeting of the Cognitive Science Society

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Journal

Proceedings of the Annual Meeting of the Cognitive Science Society, 40(0)

Authors

Yeo, Amelia

Cook, Susan Wagner

Nathan, Mitchell J

et al.

Publication Date

2018

Instructor gesture improves encoding of mathematical representations

Amelia Yeo (ayeo@wisc.edu)

Department of Psychology, University of Wisconsin-Madison, Madison, WI 53706

Susan Wagner Cook (susan-cook@uiowa.edu)

Department of Psychological and Brain Sciences, University of Iowa, Iowa City, IA 52242

Mitchell J. Nathan (mnathan@wisc.edu)

Department of Educational Psychology, University of Wisconsin-Madison, Madison, WI 53706

Voicu Popescu (popescu@purdue.edu)

Department of Computer Science, Purdue University, West Lafayette, IN 47907

Martha W. Alibali (martha.alibali@wisc.edu)

Department of Psychology, University of Wisconsin-Madison, Madison, WI 53706

Abstract

We examined the effect of instructor gesture and distractor presence on students' encoding of slope and intercept in graphs of linear functions. In Experiment 1, participants watched an instructor avatar introduce a linear graph while either pointing to the intercept, tracing the over-and-up increase for slope, or not gesturing (i.e., gaze only). They then reconstructed the graph on paper. Participants were significantly more successful at encoding slope after watching the slope gesture than after watching no gesture. In Experiment 2, participants watched the avatar either point to the intercept or trace the slope, each either in the presence or absence of a visual distractor. Participants were significantly more successful at encoding slope after watching the tracing gesture than after watching the pointing gesture. Distractor presence did not affect performance. Taken together, these results suggest that teachers' gestures promote students' encoding of relevant information and could help explain why teachers' gestures often benefit students' learning.

Keywords: gesture; multimodal instruction; education; learning; memory

Introduction

Many studies have shown that teachers use gestures during instruction (e.g., Alibali & Nathan, 2007; Nathan & Alibali, 2011). These gestures have been found to benefit students' learning. For example, Church, Ayman-Nolley and Mahootian (2004) reported that first-grade students displayed deeper learning about Piagetian conservation from a lesson containing speech and gesture, as compared to a speech-only lesson. Additionally, Valenzeno, Alibali and Klatzky (2003) found that preschoolers learning about symmetry were better at solving posttest problems when they had watched the lesson with speech and gesture, as compared to a speech-only lesson. On the topic of mathematics, Alibali et al. (2013a) found that lessons were more effective when the teacher used both speech and gesture together to convey concepts, rather than using only speech.

What is the basis for this benefit of gestures on learning outcomes? One possibility is that teachers' gestures guide students' attention to the referents of those gestures (see, for example, Atkinson, 2002). When teachers gesture to mathematical representations, students may be more likely to attend to and appropriately encode the information, and this may lead to greater learning of lesson content. If this is the case, then variations in teachers' gestures should lead to variations in students' encoding of instructional material.

Teachers can use a range of gestures to direct students' attention during a lesson. Prior research on teachers delivering a mathematics lesson found that pointing and tracing were especially prevalent in instruction (Alibali et al., 2013b; Alibali et al., 2014). Specifically, in an algebra lesson on mapping between an equation and a graph, pointing was used to direct attention to the intercept of the graph on a whiteboard. Tracing, on the other hand, was observed to be used by the teacher to highlight the slope of the linear graph by depicting the increase of the variable on the y-axis as a function of a unit increase in the variable on the x-axis. If these specific gestures support students' learning by enabling them to encode better, then pointing gestures directed to the intercept of a graph should lead to better encoding of the intercept than tracing gestures depicting the over-and-up unit increase of the slope, and vice versa.

In a first experiment (Experiment 1), we examined this prediction. We analyzed participants' encoding of the intercept and slope of a linear function after students had watched video clips containing these different forms of instructor gesture. We expected students to be more successful at encoding the intercept or slope, depending on which gesture the instructor used in the clip, over and above a baseline condition with no gesture at all.

We also examined whether the presence of distracting, irrelevant information might enhance the role of gesture in promoting accurate encoding. During a lesson, visually

distracting information is not uncommon (e.g., graphs that were drawn to make a previous point; poorly-erased past material). Extraneous visual information could distract students' attention as they attempt to focus on the lesson. If gestures promote encoding, they might be particularly helpful in the presence of potentially distracting information. In a second experiment (Experiment 2), we examined whether the presence of a visual distractor together with instructional gesture would influence students' encoding. We predicted that students would be more successful at encoding slope after watching the over-and-up tracing gesture than after watching the pointing-to-intercept gesture, and further, that this effect would be larger in the presence of a distractor. We also predicted that students would be more successful at encoding intercept after seeing the pointing gesture than after watching the tracing gesture, and that this effect would be larger in the presence of a distractor.

To date, most research into the role of gestures on student learning has used lessons presented by human teachers. However, "live" teachers cannot be blinded to the experimental conditions, so their expectations might affect the data (e.g., Good, 1987). Furthermore, producing scripted gesture is difficult, and might incur a cognitive load that affects speech and other behavior. In this study, we examine the role of gesture on learning using a computer animated pedagogical agent (i.e., an instructor avatar). Using a programmable avatar allows for full control of speech, gaze and gesture trajectories, which are very difficult to control with a human actor in a video. Full control over these factors supports isolating the cause of any performance differences found in the experiments.

Experiment 1

Participants

The participants were 60 native English speakers (39 female). All were recruited from an Introductory Psychology course, and they were compensated with extra credit.

Materials

Three sets of animated videos were created for this experiment. Each set consisted of five videos containing linear graphs presented on a whiteboard (Figure 1). Each video lasted for six seconds and the avatar introduced the graph in each video by uttering, "Look at this line". In one set of videos, the avatar produced the utterance without gesturing. In another set of videos, the avatar pointed to the y-intercept of the graph, and in the final set of videos, the avatar traced the unit increase of the slope (i.e., by producing an "over-and-up" tracing gesture). The duration of the pointing gestures in both sets of videos was approximately 3 seconds and the duration of the tracing gestures was approximately 4 seconds. Five different linear graphs were used for the no-gesture videos. Another five

different linear graphs were generated for the pointing and tracing gesture videos. Thus, the graphs in the pointing videos were identical with the graphs in the tracing videos, but these graphs differed from the graphs in the no-gesture videos. Of the five linear graphs in each set, four had a positive slope and one had a negative slope. Figure 1 displays a still frame from each of the three gesture conditions.

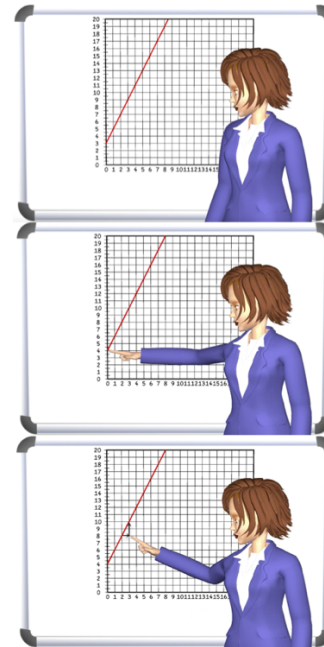


Figure 1: Example frames without avatar gesture (top), with a pointing gesture (middle) and with a gesture tracing the unit increase of the slope (bottom, depicted with the arrows that were not present in the actual stimulus).

Procedure

At the start of the experiment, participants were told that they would see videos of graphs being presented on the computer screen, and that they would be asked to draw each graph when prompted to do so through on-screen instructions. Participants were reminded to start drawing only after the graph was no longer visible on the screen. During the experiment, participants were presented with the animated videos in two blocks in fixed order. In the first block, they watched the five no-gesture videos. In the second block, participants were randomly assigned to watch either the pointing-to-intercept gesture videos or the over-and-up-tracing gesture videos. We presented participants with the no-gesture videos first in order to measure performance on the task before the influence of the avatar's gesture, as we were concerned that the effect of observing gesture could carry over to subsequent no gesture trials. Participants reconstructed the graphs using a pencil on paper (with the graph frame provided) after each video.

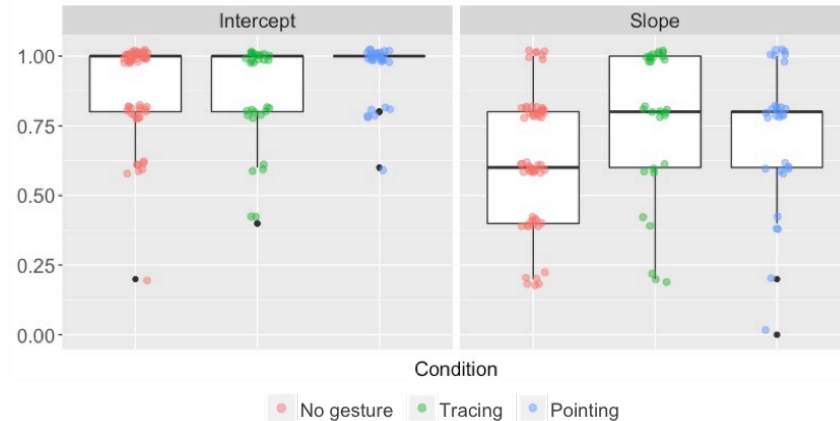


Figure 2: Plot of proportion accuracy for intercept and slope encoding across the no gesture condition (red), the tracing gesture condition (green) and the pointing gesture condition (blue).

In total, each participant watched ten videos and reconstructed ten graphs. Thus, each participant was exposed to the no-gesture condition, while half ($n = 30$) were exposed to the pointing gesture condition and half ($n = 30$) to the tracing gesture condition.

Coding

We coded whether participants produced the correct intercept and slope in their graph reconstructions. If the linear graph crossed the y-axis at the correct unit, the intercept was coded as correct. If the reconstructed graph contained the correct unit change in y as a function of x, the slope was coded as correct. Thus, each reconstructed graph was coded separately for accuracy of intercept and slope.

Results

On average, participants performed close to ceiling on encoding intercept across all three conditions (89% for the no-gesture condition; 95% for the pointing gesture condition and 86% for the tracing gesture condition). They performed less well on encoding slope, with an accuracy of 64% in the no-gesture condition, 72% in the pointing gesture condition and 77% in the tracing gesture condition. Figure 2 presents scatterplots of proportion accuracy across the three conditions, and boxplots depicting the distributions.

To analyze whether students were more successful on encoding the intercept or slope depending on which gesture the instructor used in the clip, we analyzed a series of nested binomial multilevel models. All models included participant and item as random effects; we excluded the random slope for element by participant, as models containing that term did not converge. The dependent variable was accuracy (yes/no). All analyses were conducted in R version 3.2.2.

With regard to our hypothesis, we first examined whether the interaction between gesture type (no gesture/pointing/tracing) and element (slope/intercept) accounted for variation in participants' encoding, by comparing models

with and without the interaction term¹. Including the interaction significantly improve model fit, $\chi^2(2) = 10.99$, $p = .0041$. Parameters of the model that included the interaction term indicate that this significant interaction was driven by a significant interaction between the tracing gesture and no gesture conditions with element type, $B = 1.31$, *Wald's z* = 3.05, $p = .0023$. Participants in the tracing gesture condition performed better on encoding slope on the gesture trials ($M = 0.77$, $SD = 0.05$) than on the no-gesture trials ($M = 0.65$, $SD = 0.04$). Within this model, the interaction between the pointing gesture and no gesture conditions with element was not significant, $p = .58$. Thus, there was no evidence that participants differed in their encoding of slope or intercept depending on whether they had viewed the pointing gesture or no gesture videos.

To examine whether the different gesture conditions influenced the accuracy of encoding in general, we also compared models with and without the gesture term. Including the fixed effect of gesture did not improve model fit over and above a model that included the fixed effect of element and the random effects, $\chi^2(2) = .26$, $p = .88$. Thus, there were no significant differences between the three gesture conditions in the overall accuracy of participants' encoding.

Finally, we compared a model with element as a fixed effect to a model with only the random effects. Including element improved model fit, $\chi^2(1) = 104.43$, $p = <.001$. Participants were more likely to accurately encode the intercept than the slope.

Discussion

We found that the avatar instructor's gesture influenced participants' encoding of slope. This finding is in line with our hypothesis that instructor gestures influence students' encoding of mathematical representations. Hand movements

¹ The models compared were: Accuracy ~ gesture*element + (1|participant) + (1|item) and Accuracy ~ gesture + element + (1|participant) + (1|item)

of the instructor can act as a visual information source that students can rely on to guide their attention appropriately.

Contrary to expectations, we did not detect a significant effect of pointing gestures on intercept encoding, potentially because participants' encoding of intercept was near ceiling. Apparently, reproducing the intercept was fairly easy for participants in our sample. To remedy this issue in Experiment 2, we included visual distractors in the graphs, in order to make the encoding task more difficult.

In Experiment 1, we also did not counterbalance the order of the gesture conditions; instead, we always presented the no-gesture videos first, and participants saw either the pointing videos or the tracing videos. In Experiment 2, we pitted the two gesture conditions against one another, in a fully within-subjects design.

Experiment 2

We conducted a fully within-subjects experiment with three factors: gesture type (pointing or tracing), distractor presence (yes or no), and target element (intercept or slope). We expected participants to encode slope better after seeing the over-and-up tracing gesture than after seeing the pointing gesture. We also predicted that the effect of the tracing gesture on slope encoding would be larger in the presence of a distractor. We expected participants to encode intercept better after seeing the pointing gesture. We also predicted that the effect of the pointing gesture on intercept encoding would be larger in the presence of a distractor.

Participants

Participants were 32 native English speakers (20 female). All were recruited from an Introductory Psychology course in exchange for extra credit. None of the participants had taken part in Experiment 1. Sample size as well as the number of items were determined using simulation methods, based on the findings from Experiment 1.

Materials

Four sets of stimuli were used in this study. Each set of stimuli contained five animated videos. Five different linear graphs were used in each set, and these graphs were repeated across sets. In two sets of stimuli, the avatar instructor pointed to the y-intercept on the linear graph, and in the other two sets of stimuli, the avatar instructor produced an over-and-up tracing gesture to indicate the slope of the graph. For each of the two sets of gesture videos, we created a version with distractors and a version without distractors. In each case, the distractor was a parabola beside the linear graph that did not intersect the straight line. The parabola was always located to the left of the linear graph. There were 20 videos altogether. Each video lasted for about 6 seconds. The pointing gestures lasted for approximately 3 seconds and the tracing gestures lasted for approximately 4 seconds in each video. Figure 3 displays example still frames of the pointing gesture and the tracing gesture with the distractor present. For examples of

the videos without the distractor, refer to the middle and bottom sections of Figure 1.

Procedure

The procedure was largely the same as in Experiment 1. Participants were presented with the animated videos in one of four pseudo-randomly generated orders. Participants reconstructed the linear graph using a pencil on paper after each video. In total, each participant watched twenty videos and reconstructed twenty graphs.

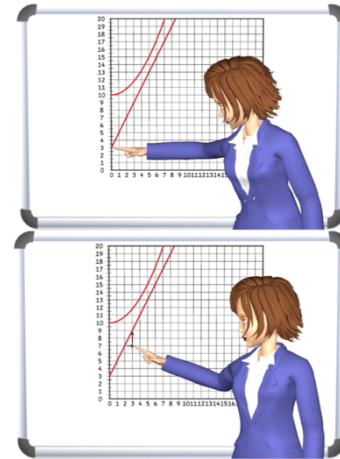


Figure 3: Example still frames with a pointing gesture (top) and with a gesture depicting the unit increase of the slope (bottom) with distractor present.

Coding

Coding was identical to Experiment 1. If the linear graph crossed the y-axis at the correct unit, the intercept was coded as correct. If the reconstructed graph contained the correct unit change in y as a function of x, the slope was coded as correct.

Results

Participants again performed near ceiling at encoding intercept (despite the distractors) and they performed less well on encoding slope. Table 1 presents the average encoding accuracy percentage across the four conditions.

Table 1: Average encoding accuracy % for intercept and slope across conditions.

Distractor	Gesture	Intercept %	Slope %
Absent	Pointing	94.4	79.4
	Tracing	91.9	80.6
Present	Pointing	93.8	73.8
	Tracing	88.8	77.5

We used a series of nested binomial multilevel model analysis to assess effects of gesture condition and distractor. The full model predicting encoding from the three-way

interaction of condition, distractor and element, with random intercepts for participants and items and a random slope for gesture condition by participant, did not converge., so we did not test the three-way interaction. Because items were presented in pseudo-random orders, we also included order as a fixed effect in our models. All models included participant and item as random effects, along with a random slope for gesture condition by participant. The dependent variable was accuracy (yes/no) in encoding slope.

Because intercept encoding was again close to ceiling levels, we focused our subsequent analysis on slope encoding. Furthermore, because participants were very unlikely to encode slope correctly without also encoding intercept correctly (this occurred on fewer than 1% of trials), we controlled for accuracy of intercept encoding on each trial.

We first examined whether the interaction between gesture type (pointing/tracing) and distractor presence accounted for variation in participants' encoding of slope, controlling for accuracy of intercept encoding and trial order, by comparing models with the interaction term and models with only the main effects without the interaction term. Including the interaction of gesture type and distractor presence did not significantly improve model fit, $\chi^2(1) = 1.23, p = .27$.

We then tested whether distractor presence influenced participants' encoding of slope, comparing models with and without a main effect of distractor. Including the fixed effect of distractor did not significantly improve model fit, relative to a model that included only gesture type, trial order, accuracy of intercept encoding and the random effects, $\chi^2(1) = 2.80, p = .09$.

Next, we tested if gesture type influenced participants' encoding of slope, comparing models with and without a main effect of gesture type while controlling for trial order and accuracy of intercept encoding. Including the fixed effect of gesture type significantly improved model fit, relative to a model that included only trial order, intercept encoding and the random effects, $\chi^2(1) = 4.18, p = .04$. Participants were more likely to encode slope accurately after seeing the over-and-up tracing gesture than after seeing the pointing-to-intercept gesture. We also tested whether trial order influenced participants' encoding of slope.² Including trial order significantly improved model fit, relative to a model that included only gesture type, intercept encoding and the random effects $\chi^2(1) = 25.33, p < .001$; participants' encoding of slope improved across trials.

Discussion

The results suggest that instructor gesture can help students accurately encode mathematical representations. Specifically, teachers' gestures appear to support the encoding of features of mathematical representations that

are highlighted by those gestures. Students were significantly more successful at encoding the slopes of linear functions after having watched tracing gestures that indicated the slopes compared to no gesture at all and compared to gestures indicating the intercept. These findings suggest that the benefits gained from teachers' gestures may be due to the gesture improving students' attention to, and therefore their memory for, information presented in the lesson. Teachers' gestures may function as an external cue that directs students' attention, helping them to learn more effectively.

These findings show that the effect of a specific type of gesture (i.e., indicating the slope) on encoding is confined to the specific feature of the representation that it highlights. Thus, gesture is not simply drawing attention to the instructor or to the accompanying spoken language. Given findings that teacher gesture is malleable (Alibali & Nathan, 2007; Alibali et al., 2013), one implication of our work is that it might be fruitful to train teachers to gesture more purposefully by directing their gestures to align with what they actually want students to notice and remember.

On the other hand, the results did not show that pointing to the intercept led to better encoding of intercept, even though the gesture clearly directed attention to it. One possible reason for this could be that encoding the intercept was too simple a task for these participants. Because there was little variability in encoding, it was impossible for us to detect any specific effect of gesture. For students who do not have difficulty encoding the intercept, instructors' gestures likely do not matter, since they succeed anyway.

These findings highlight the possibility that not all gestures are useful for all students. Gestures that bring attention to specific referents may not be helpful if those referents are easily encoded. Indeed, previous research has shown that some instructor gestures can even be detrimental to learning (Yeo, Ledesma, Nathan, Alibali & Church, 2017). These findings emphasize the value of research into specific types of gestures and their effects for specific populations of learners. Although teachers' gestures have been reported to positively influence learning in many studies, it remains possible that some gestures may distract or may not help some students. By focusing on specific gestures and contexts, further research could help shed light on the most effective types of instructional gestures, allowing for more pointed recommendations on the use of gestures in instruction.

Contrary to our predictions, the presence of a distractor did not affect encoding of intercept or slope. One possible reason for this is that the distractor we used may not have been sufficiently attention grabbing. In the presence of a visual distractor, we might assume that encoding performance would be lower in general. We did indeed find that encoding performance was somewhat lower when the distractor was present³, $B = -0.34, Wald's z = -1.68$;

² The models compared were: Slope ~ gesture + order + intercept + (1+gesture|participant) + (1|item) and Slope ~ gesture + intercept + (1+gesture|participant) + (1|item)

³ The model used for the reported parameters was: Slope ~ gesture + distractor + order + intercept + (1+gesture|participant) + (1|item)

however, this effect was not significant with $\alpha = .05$ (refer to Results for details). Therefore, it seems that our distractor manipulation may not have been strong enough. In future studies, additional visual “noise” could be employed to yield a more sensitive test of a distractor effect. For example, future studies might employ a parabola that crosses the linear graph or other distracting items on the whiteboard (e.g., equations, shapes, etc.).

The participants in this study were undergraduates, and the pattern of findings may not generalize to younger learners. Younger students might find encoding of intercept to be a more challenging task. In that case, we could obtain more variability and could test whether the pointing gesture helps encoding of intercept in the absence of a ceiling effect. Furthermore, Hostetter (2011) reported in a meta-analysis that the effect of speakers’ gestures on listeners’ comprehension is stronger in children than in adults. Thus, if we were to examine the effect of instructor gestures on encoding in children, we might even see a stronger effect.

Past research on the effect of gestures on learning has largely used human teachers who have produced scripted lessons on video. However, human actors are susceptible to altering their voices, facial expressions and gaze when they gesture. Further, the gestures produced by actors might not always be identical across conditions. Thus, findings attributed to gestures in past work could be driven by other co-occurring behaviors. By using the programmable avatar, we have kept other behavioral cues as consistent as possible, leaving only gesture to vary. As a result, our findings can be more definitively attributed to gesture.

These findings demonstrate that the gestures of an animated avatar can benefit students’ encoding. With the increasing popularity of animated pedagogical agents, our study highlights gesture as a factor to consider when designing lessons with these agents. In line with past work that reported better student learning with agents that use multiple modalities as compared to a single modality (Luck & Atkinson, 2007), our study suggests that gestures are an important dimension to consider when designing agents that interact with students and deliver lessons. Specifically, these findings highlight how specific gestures can be used to direct students’ attention for better encoding.

Our study demonstrates that gestures are beneficial for encoding, but it does not address whether gestures are more effective than other forms of visual cues. One important future direction would be to examine whether other sorts of cues, such as prosodic cues or color coding, might also confer similar benefits, or whether such cues might interact with gestural cues to promote accurate encoding.

In conclusion, these findings suggest that students encode specific features of mathematical representations more accurately when their teachers’ gestures support encoding of those features. Thus, these findings highlight the value of teachers’ gestures in promoting appropriate encoding of instructional material.

Acknowledgments

This research was funded by grant R305A130016 from the Institute of Education Sciences. We thank Meng-Lin Wu, Saikiran Anasingaraju, Sarah Brown, and Maia Ledesma for assistance with producing the stimuli. We thank Colleen Bruckner and Sara Her for help with coding.

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