The Role of Verbal and Visuospatial Working Memory in Supporting Mathematics Learning With and Without Hand Gesture

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Abstract

Gesture during math instruction supports learning in children and adults. The mechanism by which gesture enhances learning across development is not known. One possibility is that instruction with gesture engages different cognitive abilities during learning than instruction without gesture. Our previous work showed a positive relationship between visuospatial working memory capacity and learning only when gesture was present, and a positive relationship between verbal working memory capacity and learning only when gesture was absent, suggesting that gesture may be processed using visuospatial working memory. The aim of the current experiment was to replicate and extend these prior findings with new instruction, random assignment to instructional condition, and improved measures of both learning and cognitive abilities. Participants observed video instruction in a novel mathematical system that either included speech and gesture or only speech. After instruction, participants completed a posttest to assess learning. Finally, participants completed tasks to assess verbal and visuospatial working memory capacity as well as fluid and crystallized intelligence. We found that gesture benefitted learning in adults. Contrary to previous findings, both learning with gesture and learning without gesture were supported by visuospatial working memory. These findings suggest that changing characteristics of instruction does not necessarily change the cognitive resources supporting learning in a novel math task.

Keywords: gesture; learning; working memory; visuospatial; verbal; mathematics

Background

Observing gesture during mathematical instruction enhances learning in children and in adults (Cook, Duffy, & Fenn, 2013; Cook, Friedman, Duggan, Cui, & Popescu, 2016; Hendrix, Fenn, & Cook, 2018; Rueckert, Church, Avila, & Trejo, 2017; Wakefield, Novack, Congdon, Franconeri, & Goldin-Meadow, 2018). When instructors use deictic pointing gestures – hand gestures that index specific items in the learning environment – while teaching, mathematical learning is improved. The beneficial effect of observing gesture to improve mathematical learning is well established. However, the underlying mechanism of gesture as a tool for learning has yet to be elucidated.

One possibility is that gestures recruit visuospatial resources to support learning (Özer & Göksun, 2020; Wu & Coulson, 2014). Multimodal instruction may allow learners to use additional resources, while instruction that does not include gesture may force learners to rely on a more limited set of abilities. If this account holds, then the amount of learning from gesture should be related to visuospatial capacities, because this capacity would be required to take advantage of the information in gesture. While both verbal and visuospatial working memory processes have been shown to support math learning (e.g., Alloway & Alloway, 2010; Passolunghi, Vercelloni, & Schadee, 2007; Jarvis & Gathercole, 2003), it is not clear how processes that support learning relate to variations in instructional design.

In our prior work, we found evidence that instruction with gesture might rely on visuospatial resources. Math learning was positively related to visuospatial working memory capacity when the instructor gestured during instruction, and math performance was positively related to verbal working memory capacity when the instructor did not gesture during instruction (Aldugom, Fenn & Cook, 2020). These findings suggest that gesture at instruction may be particularly helpful for learners with strengths in visuospatial working memory.

However, there were several aspects of the design and implementation that limited the strength of the evidence in this prior work. Lighting and other cues that naturally co-vary with gesture such as head-turns and eye gaze were not perfectly controlled across the instructional videos. The measures of verbal and visuospatial working memory were chosen based on prior work (Chu & Kita, 2011; Wu & Coulson, 2014); however, these included a simple span task for visuospatial working memory and a complex span task for verbal working memory. Therefore, it is possible that the differential pattern of association with instruction reflected characteristics of the task (simple versus complex), rather than the nature (verbal versus visuospatial) of the task. In addition, Composite American College Testing (ACT) score was used to control for general intelligence, instead of specific laboratory measures of intelligence. Finally, instruction with gesture and instruction without gesture were investigated in separate studies. Instructional condition was confounded with semester of data collection. Thus, learning condition was not randomly assigned.

To provide a more robust investigation of how individual differences in working memory capacity supported mathematical learning when instruction includes gesture, we conducted a replication and extension. This study included with improved training materials, an enhanced assessment of learning, more comparable working memory measures, laboratory assessment of general cognitive ability, and a randomized experimental design. The goal of this work was to conceptually replicate prior findings using enhanced learning and memory measures and with an experimental design that allowed for comparison across learning conditions in a sample that has been randomly assigned to condition. Replication is essential to prevent false-positive rates as well as over-estimation of effect sizes (Murayama, Pekrun, & Fiedler, 2013; van Aert & van Assen, 2017).

Predictions

We expected to replicate and extend findings from our previous work (Aldugom et al., 2020). First, we predicted that those in the gesture condition would learn more than those in the no gesture condition. Second, we predicted that for those in the gesture condition, visuospatial working memory capacity would predict learning, whereas for those in the no gesture condition, we expected verbal working memory capacity would predict learning.

Methods

The purpose of this study was to further examine the relationship between individual differences in visuospatial and verbal working memory capacity and mathematical learning with or without gesture at instruction. Approval was obtained from the relevant institutional review board.

Participants

176 undergraduates from a large Midwestern university participated in this experiment. Participants were excluded from the final analysis for being non-Native English speakers (n=33), for missing data (n=12), or for not performing above chance in the abstract math learning task (n=33). These exclusion criteria were similar to our prior work. We elected to exclude non-native English speakers given that these speakers might recruit different resources to process the instructions, and because the working memory measures might not accurately measure capacity. We elected to remove participants who did perform above chance as the goal of the study was to investigate learning, and there was no evidence that these participants had learned. As a result, 98 participants (36 male, 62 female) were included in the final analyses. Of these participants, 50 were in the gesture instructional condition and 48 were in the no gesture condition. Participants received course credit for participation.

Materials

Abstract Mathematical Equivalence Task We investigated mathematical learning with or without gesture using new materials based on the abstract mathematical equivalence task from our prior work (Aldugom et al., 2020). This novel mathematical task was developed for studying mathematical learning in a laboratory setting (originally adapted from Kaminski, Sloutsky, & Heckler, 2008). This task requires participants to solve problems in a commutative group of order three operating over shapes (triangle, circle, and square) (see Fig. 1). Due to the novelty of the materials, which were created for this study based on prior work, we could be certain that participants had no experience with this math system or the rules necessary to solve the problems. There is no way to infer the correct interpretation of the novel symbols without instruction or feedback. Accordingly, we gave participants instruction in the novel symbol system, and then tested learning after instruction.

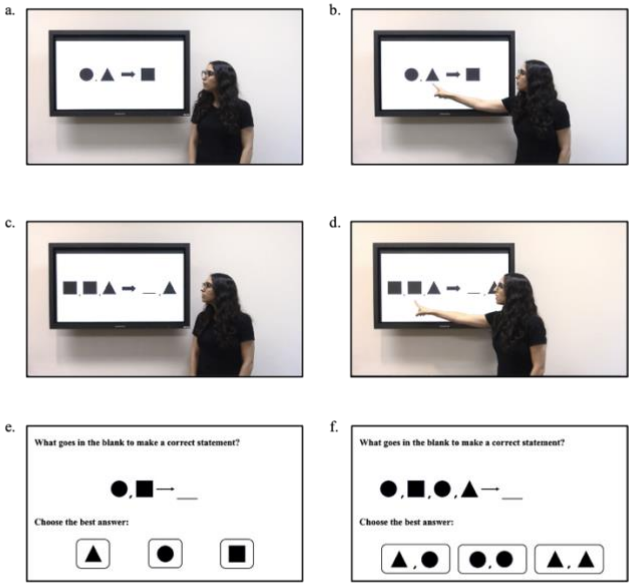

Figure 1. Example images from the updated abstract math task. a. Screenshot from an example rule video *without* gesture. b. Screenshot from an example rule video *with* gesture. c. Screenshot from an example instructional video *without* gesture. d. Screenshot from the same example instructional video *with* gesture. e. An example practice problem from the rule portion. f. An example posttest problem of the most complex problem type.

For this study, we created new instructional materials. While the video-recorded instructions that were previously used were effective in supporting learning, an in-depth examination of the videos revealed that lighting and cues that co-vary with gesture such as head-turns and eye gaze could be better controlled. Head-turns and eye gaze can cue learners to important information on the display (Ouwehand, van Gog, & Paas, 2015; van Wermeskerken & van Gog, 2017).

Therefore, it is critical to control these cues when examining the effect of gesture on learning. During video recording, the instructor stood in the same position and head-turns and eye gaze were carefully controlled across conditions.

In prior work, the six rules of the novel mathematical system were presented via text, whereas six instructional problem-solving explanations were presented in video format that either included or did not include gesture. We thought that increasing the amount of gesture in the instruction might increase the effect of gesture on learning, increasing our overall power and facilitating investigation of individual differences in this study and in future work. Accordingly, we recorded videos explaining the six rules as well as eight problem-solving explanations using these rules (two instructional explanations were added) for a total of 14 videos in each learning condition.

After recording our new set of videos, all videos went through an extensive editing process in Final Cut Pro to enhance matching and overall appeal (Meakins, 2009). All audio files were first edited to remove background noise and white noise as much as possible. We then overlapped the audio files of the gesture and no gesture pairs of each video in order to best compare each video. Then, moments of silence in either the gesture or no gesture videos were sped up or slowed down in a naturalistic manner until the speech in both videos was in sync. Once the audio files of the pair of videos matched one another, we used several video filters to enhance the visual quality of our videos, including adjusting brightness and contrast. After exporting our videos, we played each gesture-no gesture pair at the same time to ensure that the video pairs were as identical as possible, aside from the presence or absence of gesture. Thus, with this new set of videos, we have more videos (14 videos in each condition instead of six videos in each condition), and all videos were recorded and edited to enhance match and enhance overall video and audio quality.

We also improved the reliability of our measure of learning. Our prior measures of learning included a 27-item posttest and a 12-item transfer test. This original transfer test was quite similar to the posttest, and there were not significant differences between performance on the posttest and performance on the transfer test or in how they related to the working memory measures. Performance on the transfer test simply did not add to the understanding of learning beyond what performance on the posttest suggested. Therefore, we decided to remove the transfer test and add eight questions to the posttest. Specifically, we created additional problems of the more complex problem types. Increasing the number of items is one way to increase the reliability of a measure.

The instructional portion of the experiment proceeded as follows. First, participants watched six video-recorded rules for combining the three shapes in this mathematical system (Fig. 1a and 1b). Each video played one at a time. In each video, the instructor teaches one of the six rules. For example, in the third rule video (refer to Fig. 1a and 1b), the instructor states “Circle combined with triangle makes square.” In the gesture condition, the instructor points with her index finger to each shape as she says the name of the shape. In the no gesture condition, the instructor’s hands rest by her sides. In both sets of videos, head-turns and eye gaze to the problem are matched. The videos ranged from 12 seconds to 37 seconds. After viewing each video, participants answered one or two practice problems before seeing the next rule (Fig. 1e). The practice problems were simple equations, the result of the combination of two symbols. Participants need this basic understanding of the rules in order to succeed in practice problems and in the posttest.

After viewing the six rule videos and solving six simple practice problems, participants then watched eight video-recorded explanations of how to solve more complex problems in this same mathematical system (Fig. 1c and 1d). These more complex problems were based on math problems designed to assess the understanding of mathematical equivalence in children and required an understanding of how the rules apply to problems with five symbols. In each of the video-recorded explanations, the instructor explains how to solve a problem and fill in the blank with the correct symbol. For example, in the third instructional video (refer to Fig. 1c and 1d), the instructor states “Square combines with square to make square, and square combines with triangle to make triangle, so one side reduces to make triangle. I already have a triangle on the other side, so what combines with triangle to make triangle? The answer is square.” In each gesture video, the instructor points to each shape as it is named in speech. Thus, all of the gestures in the video-recorded explanations in the gesture condition were deictic gestures. For the matched video-recorded explanations in the no gesture condition, the instructor casually kept her arms at her side, but turned her head and body to gaze at the board identically to the head and body movements in the gesture condition. Thus, each video contained the same content and speech; the only difference was the presence or absence of gesture. The video-recorded explanations ranged from 15 seconds to 27 seconds. After each video-recorded explanation, participants solved one practice problem that had a similar form to that of the video.

After watching eight video-recorded explanations and solving eight practice problems, participants were given a 35-question posttest to assess learning (Fig. 1f). Posttest problems were presented in a fixed order of approximately increasing difficulty. All problems in the posttest were novel, so participants did not see any of the posttest problems during training. The posttest problems ranged in complexity, and all problems were scored as correct or incorrect.

Symmetry Span Task To assess visuospatial working memory capacity, we used the shortened version of the symmetry span task (Shah and Miyake, 1996). This task included a processing task and a memory task. On each item, participants were presented with an 8 x 8 matrix with some squares filled in with black. Participants were asked to judge whether the geometrical image was symmetrical. They were then shown a 4 x 4 matrix with one red square filled in. After between 2 and 5 items (symmetry judgment + spatial memory), participants were asked to recall the location of the red squares that they held in memory in the order in which they appeared (Oswald, McAbee, Redick, & Hambrick, 2015). Coefficient alpha was .59.

Raven's Advanced Progressive Matrices To assess fluid intelligence, we used the Raven's Advanced Progressive Matrices (Raven, 2000). Participants were shown a pattern of eight black and white figures arranged in a 3 x 3 matrix. In each pattern, one figure was missing, and the participant's task was to choose the figure that best completed the sequence (from among eight items). There were 18 items in this test and participants were given 10 minutes to complete the test.

Reading Span Task To assess verbal working memory capacity, we used the shortened version of the reading span task (Daneman & Carpenter, 1980). As in the Symmetry span task, this task included a processing task and a memory task. On each item, participants were given a sentence and had to judge whether or not the sentence made sense. They were then given a letter to remember. After between 4 and 6 items (sentence judgement + letter memory), participants were asked to recall the letters, in order (Oswald et al., 2015). Coefficient alpha was .54.

Vocabulary Task To assess crystallized intelligence, we used a vocabulary task. For the first set of items (n=10), participants were given a word and were asked to choose (among 5 options) the word that was the closest synonym with the given word. For the second set of items (n=10), participants were given a word and were asked to choose the word that was the closest antonym of the given word. They were given five minutes to complete the synonym test and five minutes to complete the antonym test.

Abbreviated Math Anxiety Scale (AMAS) We were interested in exploring the possibility that gesture might interact with math anxiety and so we included a measure of math anxiety. We used the Abbreviated Math Anxiety Scale (Hopko, Mahadevan, Bare, & Hunt, 2003). Participants completed a 9-item questionnaire that assessed anxiety levels related to specific mathematical situations. Internal consistency within the measure was high (α = 0 .90). This measure was used for exploratory purposes and these data will not be discussed in the present paper.

Procedure

Participants were randomly assigned to the gesture or the no gesture group of the abstract mathematical task (1:1 randomization). Participants completed the tasks in the order that they are described here. At the end of the experiment, participants completed a short participant information questionnaire. Data from all tasks were collected on a computer in a laboratory setting.

Results

We first compared participants across learning conditions (gesture vs. no gesture) to assess whether there were group differences in the individual differences measures. There were no group differences in fluid intelligence, crystallized intelligence, verbal working memory, or visuospatial working memory (see Table 1). Given random assignment, we did not expect to find differences.

We measured learning using accuracy in solving problems on the posttest. We then modeled the extent to which visuospatial working memory capacity and verbal working memory capacity predicted learning, while controlling for fluid and crystallized intelligence.

Prior to analysis, we assessed multicollinearity of predictors. We examined the bivariate correlations among predictors. The bivariate correlation between verbal working memory and visuospatial working memory was weak (r = .36). There were also weak correlations between fluid intelligence and verbal working memory (r = .19), fluid intelligence and visuospatial working memory (r = .36), crystallized intelligence and verbal working memory (r = .19), and crystallized intelligence and visuospatial working memory (r = .09). Finally, the bivariate correlation between fluid and crystallized intelligence was also weak (r = .29). To further reduce collinearity in our analysis, and to be consistent with prior work, we calculated the residual of the regression of working memory values predicted from both fluid and crystallized intelligence to ensure that our working memory measures only measured working memory and not other cognitive abilities.

Mean performance on the posttest was 0.82 (SD =.16) for participants in the gesture condition and 0.77 (SD =.16) for those in the no gesture condition, suggesting that our participants were successful in learning from the new instruction. Following prior work, we modeled the log odds of correctly solving each posttest problem from two-way interactions between condition and verbal working memory, and condition and visuospatial working memory, with fluid and crystallized intelligence as covariates, and participant and problem intercepts as random effects. Gesture was dummy coded, with the no gesture condition serving as the reference group.

There were positive main effects of fluid intelligence (β = 0.44, z = 3.14, p = 0.002), and crystallized intelligence (β = 0.34, z = 2.55, p = 0.011) on posttest accuracy. There was also a significant effect of gesture condition (β = 0.54, z = 2.10, p = 0.036). There was also a positive effect of visuospatial working memory on posttest accuracy (β = 0.47, z = 1.97, p = 0.049). Because we used dummy coding of condition, with the No Gesture group as the reference group, this effect indicates that visuospatial working memory capacity predicted performance in the no gesture group.

The effect of verbal working memory capacity on performance was not significant (β = 0.24, z = .90, p = 0.37), indicating that verbal working memory capacity did not predict performance in the no gesture group.

Table 1: Mean (*M)* and standard deviation *(SD)* for all measures by condition.

	Rules		Explanations		Posttest		Fluid Intelligence		Crystallized Intelligence		Visuospatial Working Memory		Verbal Working Memory	
Condition	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Gesture	0.97	0.06	0.80	0.18	0.82	0.16	9.94	3.46	7.00	3.85	15.0	5.70	23.0	4.69
No Gesture	0.97	0.07	0.75	0.19	0.77	0.16	10.2	2.72	6.44	3.00	15.7	4.41	24.0	3.96

There was not an interaction of visuospatial working memory with condition (β = -0.15, z = -0.51, p = 0.61), indicating that the effect of visuospatial working memory on performance in the gesture group was not significantly different from that seen in the no gesture group. Similarly, there was not an interaction of verbal working memory and condition (β = -0.42, z = -1.19, p = 0.23). Thus, there was no evidence that the effect of visuospatial and verbal working memory varied across the two instructional conditions.

When we re-parameterized the model using the gesture group as the reference group, the overall pattern of findings for the effects of working memory were similar. There was a marginal effect of visuospatial working memory on posttest accuracy (β = 0.31, z = 1.75, p = .08), and no interaction with condition (β = 0.15, z = 0.51, p = .61). There was no effect of verbal working memory on posttest accuracy performance (β = -0.17, z = -0.77, p = .44), and no interaction with condition (β = 0.42, z = 1.19, p = 0.23).

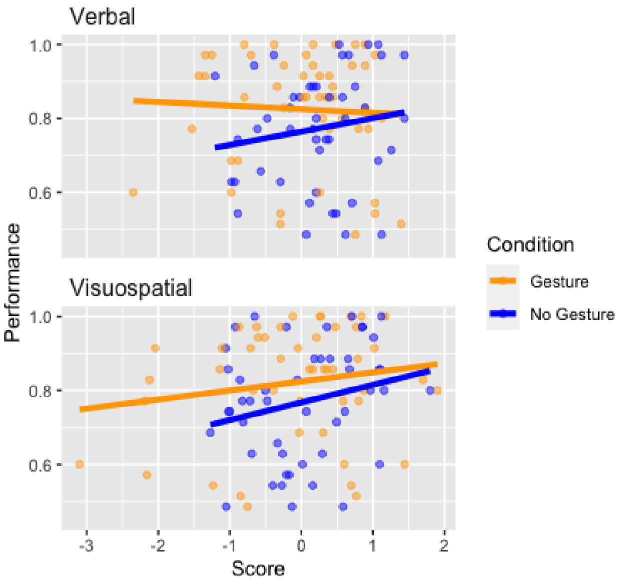

Figure 2. Verbal (top) and visuospatial (bottom) working memory scores and their relation to mathematical learning with or without gesture at instruction.

We next considered an exploratory model that did not control for fluid and crystallized intelligence, using total score for the measures of verbal and visuospatial working memory rather than residualized scores. We saw the same pattern of findings. There was a beneficial effect of gesture (β =.59, z = 2.13, p = 0.033). Visuospatial working memory predicted performance (β = .59, z = 2.38, p = 0.018) and there was no interaction with condition (β =-.22, z = -.70, p = .48). Verbal working memory did not significantly predict performance (β = .43, z = 1.55, p = 0. 12), and there was no interaction with condition (β =-.48, z = -1.28, p = 0.20). Thus, it did not seem that the pattern of findings we observed was due to controlling for intelligence included in the model.

Discussion

This experiment replicated and extended prior work that examined individual differences in working memory and how they relate to mathematical learning with gesture (Aldugom et al., 2020). We found a main effect of gesture on learning, with those in the gesture condition learning more than those in the no gesture condition. This finding extends prior work, which found only a trend towards improved performance in the gesture group in a similar version of this task. We also found both fluid and crystallized intelligence to predict posttest performance, replicating prior findings that linked intelligence to performance on this novel math task. Finally, we found that visuospatial working memory predicted posttest performance in both conditions, partially replicating prior findings.

There was a reliable benefit to learning with gesture. The adds to recent literature demonstrating that the beneficial effect of gesture on learning is not limited to children (Cutica & Bucciarelli, 2008; Kelly, McDevitt, & Esch, 2009; Pi, Zhang, Zhu, Xu, Yang, & Hu, 2019; Rueckert et al., 2017). Gesture goes beyond supporting learning in developing language learners, to support learners with more developed linguistic capabilities.

Both fluid and crystallized intelligence significantly predicted posttest performance. Considering our math task is a novel abstract equivalence task that uses shapes instead of numbers, performance on this task depends heavily on the ability to apply strategy to solve novel rule-based problems. Therefore, we were not surprised to see that measures of intelligence strongly predict performance.

Visuospatial working memory capacity was positively related to performance, and this effect was seen for both instruction with gesture and instruction without gesture. In our prior work, visuospatial working memory capacity was differentially related to performance depending on whether the instruction included gesture (Aldugom et al, 2020). Specifically, for those who learned with gesture, visuospatial working memory capacity positively predicted performance. However, for those who learned without gesture, visuospatial working memory capacity did not predict performance.

It is possible that this task relies on visuospatial working memory regardless of the presence or absence of gesture, and that our prior work simply failed to detect this effect, perhaps because we used a simple span task. It is also possible that changes in the experimental design increased the role of visuospatial working memory in supporting learning in this task. One critical difference in our experimental design was increasing the number and enhancing the visual characteristics of the instructional videos. The videos used in this experiment may have loaded on visuospatial working memory differently than the videos in our prior work.

Verbal working memory did not significantly predict performance in either condition. This finding contradicts work in the literature linking verbal working memory to math learning (Jarvis & Gathercole, 2003), although some studies have found visuospatial working memory to be more predictive of mathematical performance than verbal working memory as seen here (Giofre, Donolato, & Mammarella, 2018). This finding also contradicts our prior work, which found that verbal working memory predicted learning when instruction did not include gestures. Although the pattern observed did not show significant differences in how verbal working memory capacity related to learning, the trends in the data were consistent with our prior work. The current study may have been underpowered to detect the predicted interaction.

Because we changed the instructional videos, the posttest, and the verbal working memory measure, it is also possible that changes in the experiment design may have decreased the role of verbal working memory in supporting learning in this task. One specific change that may have altered the role of verbal working memory in this task is the presentation format of the rules. In our prior study, the rules for combining the shapes were presented in text format. Participants read each rule for how the shapes combined and related to one another and answered one practice problem after reading each rule. Participants had unlimited time to read each rule. In the present work, participants did not rely on text to understand the basic rules of this novel mathematical system. Instead, these were presented with video. It is possible that the text presented rules resulted in more verbal working memory load than video presentation.

Recent work has shown that individuals with higher visuospatial working memory are better at processing information from gestures whereas individuals with higher verbal working memory are better at processing information from speech (Özer & Göksun, 2020). Additionally, gesture sensitivity is related to visuospatial working memory, but not to verbal working memory (Wu & Coulson, 2014). These findings are consistent with the findings from our prior work, but not with some of our present data.

However, there are several key differences to note. First, the task in Özer and Göksun (2020) required participants to process simple gestures and single action words, while this task focused on multimodal processing and comprehension. The task in Wu and Coulson (2014) included short video clips of everyday activities in which gestures were either congruent or incongruent with concurrent speech, and the task required participants to decide whether picture probes were related or unrelated to the short video clips. The task in our work is an abstract mathematical learning task that operates over shapes, and the purpose of the task is to assess whether gesture enhances mathematical learning. Second, the gestures used in Özer and Göksun (2020) and in Wu and Coulson (2014) were iconic hand gestures, whereas all of the gestures used in our work are deictic (pointing) gestures. Finally, the videos used in Özer and Göksun (2020) only included the hand gestures in the visual scene. The videos used in Wu and Coulson (2014) included a speaker from the waist up in the visual scene, however, the face of the speaker was blurred. The videos used in our abstract mathematical learning task include the mathematical problem on a screen as well as the instructor from the waist up, and none of the visual information was blurred or cut from the visual scene (refer to Figure 1). Therefore, unlike prior work, the videos used in the current study contained a considerable amount of visual information in addition to the gestures.

It is possible that different cognitive mechanisms are utilized when processing short actions with speech and gesture compared with learning a novel abstract system with speech and gesture. Another possibility is that because our video recorded rules and instructions include significantly more visual information than gesture alone (facial features, lip movements, a large screen depicting the relevant shapes for each problem), the learning task loads significantly more on visuospatial working memory than verbal working memory, regardless of whether gesture is present or absent during instruction. Additional work will be necessary to understand how characteristics of learners interact with characteristics of instructional designs.

Learning arises via complex and dynamic interactions between learners and learning environments. Here, changing characteristics of instructions did not change the cognitive resources supporting learning in a novel math task, unlike findings in a previous, similar study. Given the potentially complex interplay between characteristics of learners, instructions, and tasks, researchers should be cautious in making broad claims about the generalizability of findings.

Acknowledgements

This work was supported by the National Science Foundation Grants No 1561182 and 1561122. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. We wish to thank Todd Pruner and Jeffrey Shymanski for their assistance in stimulus construction.

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