Does Click Matter?
The Role of Text and Diagram on Geometric Reasoning and Gesture Production

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Abstract

We investigate the influence of definitions with diagrams on students' mathematical reasoning for geometric insight and proof as well as on gesture production while proving geometric conjectures. Each conjecture included one technical math term hyperlinking to a definition formatted to be either all in words, or in words accompanied by a diagram to illustrate the meaning of the term. We find that clicking the hyperlink to look at the definition with a diagram was correlated with lower mathematical insight. It appears that complex geometric diagrams may yield detrimental effects on insight performance. We also find that definition with diagram can promote the production of representational gestures, which highlight interactions between available resources – in particular diagrams and gestures – in geometric reasoning.

Keywords: Geometric Reasoning, Definition, Diagram, Gesture

Objectives

Mathematical teaching and learning are increasingly viewed as multimodal processes (Arzarello, 2006; Radford, 2009), where students use different modes of representation and communication, such as oral and written text, visual forms like graphs and drawing, as well as gesture. Though these resources are used with flexibility, many of them are exploited simultaneously. Students' learning and thinking occur when they interact with and think "in and through" (Radford, 2009) these resources, illustrating the importance of examining these relationships. Gestures produced during proof construction predict proof performance (Authors, 2018). In this present study, students were asked to generate proofs for mathematical conjectures, each of which included one technical math term hyperlinking to a definition formatted to be either all in words, or in words accompanied by a diagram to illustrate the meaning of the term. We investigated whether additional text and diagram would directly influence geometric reasoning, and whether the text and diagram would impact the production of gestures, which, in turn, promote geometric reasoning.

Theoretical Framework

Learning with Text and Diagrams

Learning with text and diagrams can promote *mental model development* (e.g., Butcher, 2006), *memory* (e.g., Mayer & Gallini, 1990) as well as *deep comprehension* (e.g., Mayer & Anderson, 1992; Mayer & Gallini, 1990). Mayer's (2005, 2009) cognitive theory of multimedia learning (CTML) and Schnotz's (2005, 2014)'s integrated model of text and picture comprehension (ITPC) both support the general notion that adding text and diagrams supports complementary functions to the construction of a comprehensive mental model. Using text only relies on arbitrary relations between the words and the concepts they are representing, whereas the addition of diagrams often allows direct access to spatial structure of referents that are spatial or metaphorically spatial (Eitel, Scheiter, Schuler, & Nystrom, 2013; Kang, Tversky, & Black, 2015). Thus, the effects of integrating multimedia are bound to specific conditions. For example, adding diagrams to text is particularly effective if students are poor readers (Schnotz, 2014), have low prior knowledge (expertise reversal effect; Kaluga & Singh, 2015; Schnotz, 2014), and if the diagrams were simplified to highlight crucial structural relations (Butcher, 2006), among others (Mayer, 2005, 2009; Schnotz 2005, 2009).

Interplay Between Diagram and Gesture in Mathematical Reasoning

Gesture is an integral part of cognition and communication (McNeil, 1992). Studies of gesture in mathematics learning have identified specific patterns in teacher and student use of gesture to construct and communicate mathematical meanings (e.g., Alibali & Nathan, 2012), suggesting that mathematical reasoning is embodied. Much of this work positions diagrams and gestures as pivotal semiotic resource that are correlated with each other. Châtelet (2002) proposed that "diagrams 'lock' or 'capture' gestures" (Freitas & Sinclair, 2012). Garcia and Infante (2012) noted that students used two types of gestures, both static and dynamic (see Figure 1), to reference diagrams when solving calculus problems. They found that static gestures tended to have a stronger relationship to diagramming as they were identifying and describing content shown in mathematical diagrams. In the current research, we chose to focus on diagrams as the locus of the gesture/diagram interaction to examine whether diagrams are correlated with gesture production in students' proof practices.

Hypotheses and Predictions

We investigated the relationship between scaffolded definitions and diagrams of geometric concepts on students' geometric reasoning, specifically mathematical insights and proof validity, along with their production of gestures. We formulated two research questions: (RQ1) Does using a geometric definition with diagram associate with the generation of valid proof and correct mathematical insight? (RQ2) Does using a geometric definition with diagram associate with production of gestures? From these questions, we have two accompanying hypotheses: (H1) Hypothesis 1 claims that students who used definitions with diagrams may improve their proof and insight performance; (H2) Hypothesis 2 claims that students who looked at definitions with diagrams may produce more gestures, in particular static gestures.

Methods

Participants (N=84) were undergraduate students recruited from a large Midwestern university. Experts (N=41) were advanced year math majors who had progressed beyond formal linear algebra. Non-experts (N=43) were non-STEM education majors enrolled in the teacher education program. Each participant was interviewed in a one-on-one setting in a research lab. Two mathematical conjectures were projected in succession onto a large interactive whiteboard, one regarding a two-dimensional object (triangle) and the other a three-dimensional object (sphere or cylinder). Each conjecture included one technical math term (see Figure 2) that was underlined and hyperlinked to a definition that was projected onto the same screen in a successive slide, and was formatted to be either all in words, or in words accompanied by a diagram to illustrate the meaning of the selected word. Participants were asked to judge whether each conjecture was True or False, and to provide a justification. As they considered each conjecture, participants were told that they could choose to click the hyperlink by touching the underlined word to look at the definition.

For the purpose of analysis, participants were assigned to one of two studies based on the conjectures they were shown. Study 1 participants (experts = 20; non-experts = 21) validated conjectures *Circumscribed Triangle* (2D) and *Lateral Surface Area* (3D). Study 2 participants (experts = 21; non-experts =22) validated the same *Circumscribed Triangle* (2D) conjecture and the *Great Circle* (3D) conjecture. We also collected demographic information and measures of spatial reasoning (Ekstrom, French, Harman, & Derman, 1976) (Table 1).

Data sources

Videotapes of participants' responses were coded for correct insight and mathematically valid proof (reliability $\kappa = 1.0$) Insight was coded for the presence of correct mathematical ideas for each conjecture (coded as 0/1) (see Table 2). For proof, each participant's justification was coded as valid (1) or invalid (0) based on Harel and Sowder's (2005) three criteria for valid deductive proofs: (1) show *generality* (the argument must be true for all possible cases), (2) describe *operational thought* (an argument progresses through goal-directed mental operations, and (3) exhibit *logical inference* (provide an inductive/deductive chain of reasoning).

Gestures produced during the interviews were coded first as *representational* (reliability

κ_{REP} = .948) or not. Representational gestures were defined as gestures that depict semantic content, either literally or metaphorically, by virtue of handshape or motion (Alibali & Heath, 2001). Representational gestures were coded as either dynamic or non-dynamic. *Non-dynamic gestures* reflect only static properties of the mathematical entities or ideas they are depicting. *Dynamic gestures* enact motion-based transformations of mathematical entities.

Results and Conclusion

We used the *lmer* R package to build mixed effects logistic regression models. These models were used to predict three dependent measures: (1) correct mathematical *insight*, (2) valid transformational *proof*, and (3) *gesture* production. *Participant ID* and *conjecture* were included as random effects and for all models, the base models were fit including *expertise* (expert/non), *spatial scores* (scaled 0-1), *native language status*, definition/diagram *click*, and conjecture *dimension* as fixed effects. We added *gestures* (Nathan & Walkington, 2017) and three Coh-Metrix variables previously shown to be predictive (Authors, 2019; Graesser, McNamara, Louwerse, & Cai, 2014) as fixed-effect predictors to the base model.

BASE MODEL: Y_i (insight; proof; gesture) = $\beta_0 + \beta_1 x_1(\text{ID}) + \beta_2 x_2(\text{Conjecture}) + \beta_3 x_3(\text{Expertise}) + \beta_4 x_4(\text{Spatial}) + \beta_5 x_5(\text{ESL}) + \beta_6 x_6(\text{click}) + \beta_7 x_7(\text{2D/3D}) + \varepsilon_0$

Insight

In our analysis of Study 1, we found that participants clicking on keyword definitions with or without diagrams did not significantly impact their insight performance across all models (See Table 3). However, *representational gestures* were a significant predictor (d = .75, p < .05; Model 2 in Table 3). After controlling for transformational speech, representational gesture was still significantly predictive of correct insight (d = .76, p < .05; Model 3 in Table 3).

Study 2 revealed that clicking on a definition with a diagram was negatively associated with insight performance (d = -1.34, p < .01; Model 1 in Table 3). Consistent with these initial results, Model 2 (Model 1 + representational gestures) and Model 3 (Model 2 + three Coh-Metrix speech variables) repeatedly revealed the negative effect of definition with diagram on insight (d= -1.35, p < .01; d = -1.36, p < .01, respectively). Representational gestures remained significant for insight performance in both Model 2 (d = 1.21, p < .05) and Model 3 (d = 1.19, p < .05) (Table 3).

Proof

Both studies showed that using a definition with a diagram did not have a significant effect on learners' proof performance. Two variables positively predict proof: spatial scores (d=.57, p < .05) and dynamic gestures (d=3.00, p < .01) (Model 2 in Table 4). Model 3 (Table 4) revealed that dynamic gestures predict learner' construction of valid proof (d = 2.46, p < .01). Two Coh-Metrix speech variables, intentional cohesion of situation models (SMINTEr) (d = .95, p < .05) and verb use (WRDVERB) (d = 1.19, p < .05) were significant contributors, which adds to the growing body of evidence that shows which speech patterns contribute to valid proof.

Gestures

Study 1 participants who clicked the link to look at the definition and or diagram were more likely to produce representational gestures (*d* = 1.31, $p < .01$), even when controlling for speech variables (Model 2 in Table 5, *d*=1.41, $p < .005$). These results are in agreement with Hypothesis 2. Results from Study 2, however, revealed that looking at definition with diagram did not have a significant impact on generation of representational gestures, either in initial model or model with speech variables.

Expertise was a significant predictor of non-dynamic gesture production in models without and with transformational speech (*d*=1.21, $p < .05$ in Model 2; *d*=1.65, *p*=.005 in Model 3 in Table 5).

Both Study 1 and 2 showed that providing the definition with diagram did not have a significant effect on learners' production of dynamic gestures (Table 6). However, Study 1 showed that expertise was highly associated with dynamic gesture (*d* = .97, $p < .05$; Model 1, Table 6).

Discussion

The goal of this study was to investigate the effects of a definition with diagram on mathematical insight, proof, and gesture production. Contrary to H1, clicking definitions with diagrams was significantly negatively associated with insight performance. The 3-dimensional diagram may make the task more difficult. In Study 1, clicking any definition did not impact learners' insight performance, whereas Study 2 showed a negative association. One of main differences between the two studies is that Study 1 presented a text-only definition conjecture on the lateral surface area of a 3D cylinder, whereas Study 2 provided both text and a diagram of a great circle in a sphere. Our results suggested a possibility that the 3D diagram used might have harmed student performances rather than supported them. This is consistent with previous research showing that learning is moderated by the complexity of a diagram (Butcher, 2006), with complex diagrams yielding detrimental effects especially for low-knowledge learners (Eitel et al., 2013).

In agreement with H2, clicking on definitions that included diagrams predicted learners' production of representational gestures in Study 1. Further studies are needed to investigate under which conditions, text and visual materials may elicit or suppress gesture production, and which kind of gesture might be elicited while which are suppressed.

Limitations & Significance

Several limitations of this study should be considered when interpreting these results. Primarily, the findings are correlational and therefore do not reveal the causal relations. Second, one conjecture (i.e., *Lateral Surface Area* in Study 1) linked to a definition only, while other three conjectures each linked to a definition accompanied by a diagram.

Despite its limitations, this study showed that the text definition accompanied by a diagram could play a substantial role in students' geometric reasoning and proof formulation, which highlights considerations for design and the evaluation of multimedia in proof practices. Researchers and teachers should carefully consider whether and how multimedia materials can effectively support student performance of the process critical to learning. Likewise, this study revealed the influence of text with diagram on production of representational gesture, which will help designers consider how teachers can support these links between multimedia materials and gestures as they facilitate embodied activities.

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Figures and Tables

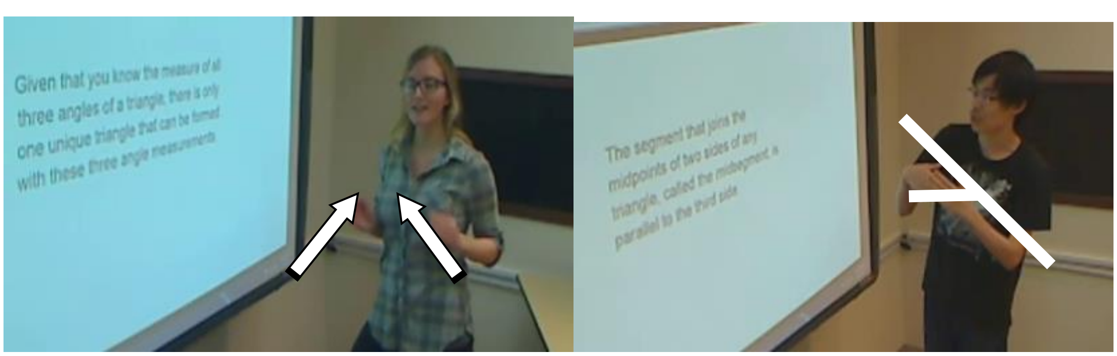

Figure 1. Participant (left) uses dynamic gesture to explore how changing the size of triangles does not change angle size, while a participant (right) uses a static gesture to explore the midsegment for one side of a triangle.

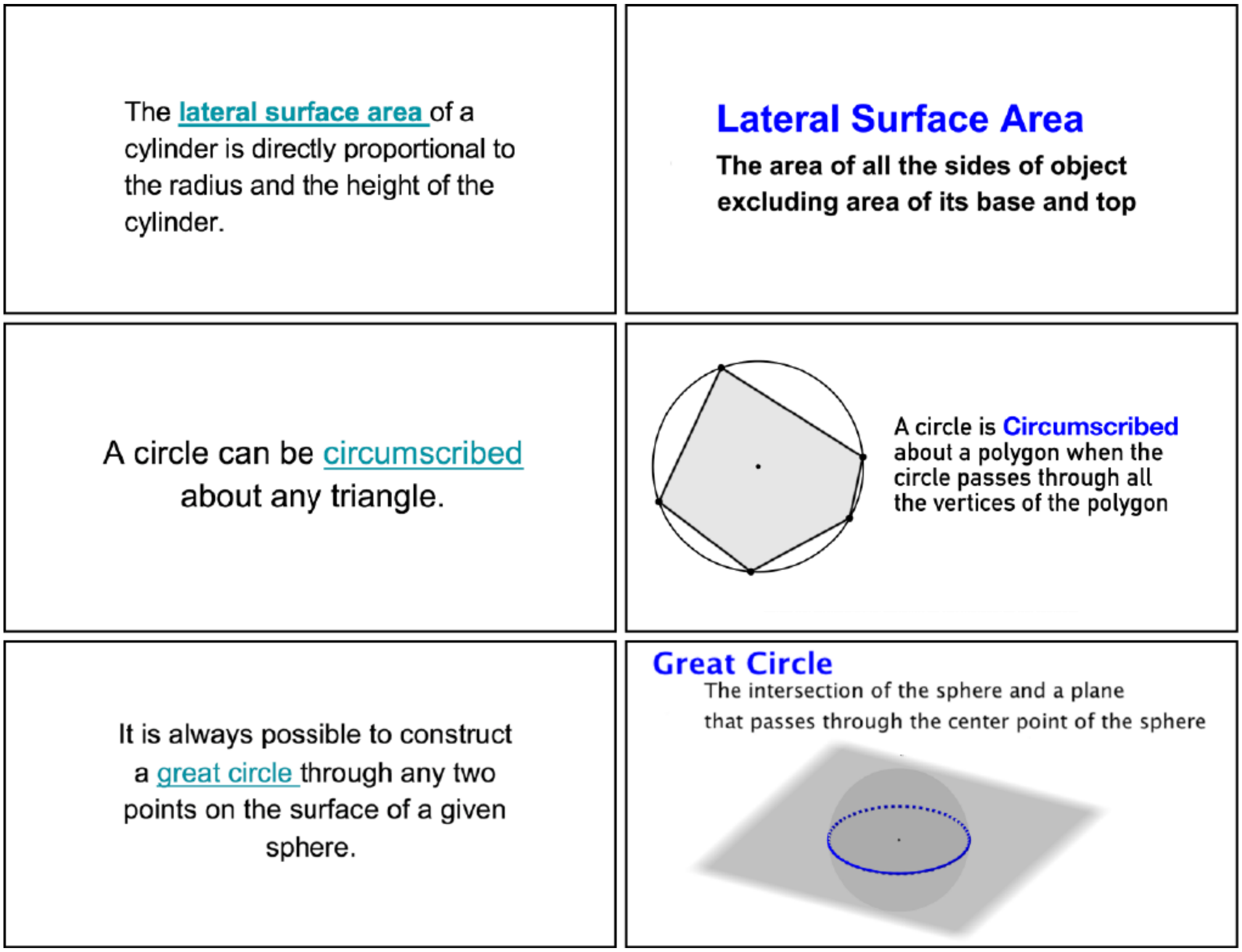

Figure 2. Mathematical conjectures with underlined technique math terms (i.e., blue words) (left) and accompanying definitions that was formatted to be either all in words, or in words with a diagram (right).

Table 1. Descriptive statistics for Study 1 and Study 2

	Study 1		**Study 2**	
	Expert (n=20)	**Non-Expert** (n=21)	**Expert** (n=21)	**Non-Expert** (n=22)
Gender	4 Female 16 Male	17 Female 4 Male	7 Female 14 Male	20 Female 2 Male
Average Age (SD)	22.05(2.76)	21.05(2.92)	21.48(3.07)	20.23(1.26)
% native English speakers	55.00%	100.00%	47.62%	95.45%
Average spatial score (SD)	7.51(1.90)	5.15 (2.03)	8.71(1.12)	4.18(2.30)
Likelihood of click	70.00%	88.10%	80.95%	88.64%

Likelihood of correct proof	17.5%	9.52%	16.67%	6.82%
Likelihood of correct insight	62.50%	47.63%	47.62%	31.82%
Likelihood of representational gesture	77.50%	61.90%	83.33%	61.36%
Likelihood of non-dynamic representational gesture	47.5%	50.00%	45.24%	52.27%
Likelihood of dynamic representational gesture	30.00%	11.90%	38.10%	9.09%

Note. SD = standard deviation

Table 2. The Insight for the three mathematical conjectures used in the study

	Name	Conjecture Text	Insight
1	Circumscribed Triangle	A circle can be circumscribed about any triangle	Conjecture is True
2	Lateral Surface Area	The lateral surface area of a cylinder is directly proportional to the radius and the height of the cylinder.	Conjecture is True
3	Great Circle	It is always possible to construct a great circle through any two points on the surface of a given sphere.	Conjecture is True

Table 3. Results of the Logistic Regression Predicting Mathematical Insight

	Study 1					Study 2				
Model 1: Main Effects										
Variables	**β**	**SE**	***d***	**p**		**β**	**SE**	***d***	**p**	
(Intercept)	-0.51	1.11	-0.28	.648		2.43	1.36	1.34	.07428	
Expert	0.28	0.60	0.15	.640		0.75	0.85	0.41	.38371	
Spatial	0.10	0.12	0.06	.412		-0.03	0.15	-0.02	.82225	
Native Speaker	-0.21	0.72	-0.12	.770		-0.23	0.69	-0.13	.74264	
Definition/diagram click	-0.07	0.62	-0.04	.914		-2.43	0.87	-1.34	.00535	**
3D Conjecture	0.31	0.46	0.17	.495		-1.68	0.54	-0.93	.00172	**
Model 2: Main Effects with Gesture										
(Intercept)	-0.97	1.14	-0.54	.3961		0.57	1.54	0.31	.71140	
Expert	-0.01	0.60	-0.01	.9872		0.13	0.97	0.07	.89312	
Spatial	0.12	0.12	0.07	.3097		0.05	0.17	0.03	.76821	
Native Speaker	-0.29	0.72	-0.16	.6875		-0.31	0.74	-0.17	.67060	
Definition/diagram click	-0.69	0.69	-0.38	.3177		-2.45	0.95	-1.35	.00959	**
3D Conjecture	0.34	0.47	0.19	.4711		-1.78	0.69	-0.98	.00985	**
Representational Gesture	1.35	0.61	0.75	.0283	**	2.19	0.91	1.21	.01690	*
Models 3: Main Effects with Gesture and Speech										
(Intercept)	-1.07	1.19	-0.59	.371		1.25	1.79	0.69	.48301	

Expert	0.01	0.71	0.01	.983		0.59	1.10	0.33	.58890	
Spatial	0.13	0.14	0.07	.361		-0.07	0.19	-0.04	.70242	
Native Speaker	-0.24	0.74	-0.13	.747		-0.40	0.81	-0.22	.62438	
Definition/diagram lick	-0.71	0.73	-0.39	.332		-2.46	0.91	-1.36	.00698	**
3D Conjecture	0.36	0.47	0.20	.452		-2.10	0.65	-1.16	.00134	**
Representational Gesture	1.37	0.62	0.76	.029	*	2.15	0.98	1.19	.02806	*
SMINTEr	-0.13	0.28	-0.077	.646		0.67	0.36	0.37	.06463	
Verbs	-0.01	0.32	-0.01	.970		0.62	0.41	0.34	.12650	
1st Person Pronouns	0.18	0.29	0.10	.538		-0.78	0.40	-0.43	.05072	

Table 4. Results of the Logistic Regression Predicting Transformational Proof

	Study 1					**Study 2**				
Model 1: Main Effects										
Variables	***β***	**SE**	***d***	**p**		***β***	**SE**	***d***	**p**	
(Intercept)	-25.33	5919.1	-13.99	.9966		-4.93	5.54	-2.72	.374	
Expert	-0.41	1.03	-0.23	.6919		-3.14	3.85	-1.73	.414	
Spatial	0.49	0.27	0.27	.0710		0.68	0.73	0.40	.353	
Native Speaker	-1.15	1.04	0.64	.2698		-2.56	2.63	-1.41	.330	
Definition/diagram click	19.45	5919.1	10.75	.9974		-2.64	2.36	-1.46	.262	
3D Conjecture	2.73	1.13	1.51	.0156	*	0.19	1.11	0.10	.861	
Model 2: Main Effects with Gesture										
(Intercept)	-30.29	2896.3	-16.73	.99165		-68.38	453.27	-37.78	.880	
Expert	-3.56	2.09	-1.97	.08452		-96.45	198.92	-53.29	.628	
Spatial	1.03	0.47	0.57	.02885	*	12.88	57.44	7.12	.822	
Native Speaker	-2.99	1.76	-1.65	.08977		-49.88	122.99	-27.56	.685	
Definition/diagram click	19.42	2896.3	10.73	.99465		-22.45	111.28	-12.40	.840	
3D Conjecture	5.10	2.05	2.82	.01296	*	-8.67	124.93	-4.79	.945	
Representational Gesture	5.43	1.98	3	.00602	**	61.07	90.28	33.74	.499	
Models 3: Main Effects with Gesture and Speech										
(Intercept)	-68.42	2048.0	-37.80	.9733		-5.16	3.95	-2.85	.1906	
Expert	-13.90	8.13	-7.68	.0873		-4.13	2.26	-2.28	.0679	
Spatial	4.17	2.37	2.30	.0786		0.67	0.49	0.37	.1690	
Native Speaker	-11.82	1.24	-6.53	.0791		-1.31	1.23	-0.72	.2866	
Definition/diagram click	29.41	1.44	16.25	.9885		-1.98	1.44	-1.09	.1713	**
3D Conjecture	19.56	1.25	10.80	.0749		-0.15	1.25	-0.08	.9058	
Representational Gesture	19.77	1.58	10.92	.0789		4.46	1.58	2.46	.0048	**
SMINTEr	-5.34	0.73	-2.95	.1269		1.72	0.73	0.95	.0186	*
Verbs	1.71	0.99	0.95	.3501		2.15	0.99	1.19	.0296	*
1st Person Pronouns	-0.86	1.31	-0.48	.5105		-0.84	0.64	-0.46	.1898	

Table 5. Results of the Logistic Regression Predicting Representational Gestures

	Study 1					Study 2				
Model 1: Main Effects										
Variables	**β**	**SE**	***d***	**p**		**β**	**SE**	***d***	**p**	
(Intercept)	-1.16	1.46	-0.64	.42695		0.21	1.17	0.12	.856	
Expert	1.67	0.92	0.92	.06950		2.19	0.90	1.21	.015	*
Spatial	-0.10	0.16	-0.06	.52189		-0.16	0.14	-0.09	.265	
Native Speaker	0.52	0.97	0.29	.59243		0.64	0.78	0.35	.409	
Definition/diagram click	2.38	0.88	1.31	.00683	**	-0.50	0.84	-0.28	.555	
3D Conjecture	-0.07	0.56	-0.04	.89636		-0.47	0.52	-0.26	.358	
Model 2: Main Effects with Speech										
(Intercept)	-1.75	1.52	-0.97	.24968		0.10	1.23	0.06	.93539	
Expert	1.53	1.00	0.85	.12630		2.98	1.06	1.65	.00506	**
Spatial	-0.00	0.18	-0.00	.99007		-0.21	0.16	-0.12	.18847	
Native Speaker	0.38	0.95	0.21	.68663		1.19	0.89	0.66	.17805	
Definition/diagram lick	2.56	0.88	1.41	.00366	**	-0.95	0.97	-0.52	.32627	
3D Conjecture	-0.07	0.57	-0.04	.89724		-0.55	0.54	-0.30	.30889	
SMINTEr	-0.12	0.34	-0.07	.72831		1.13	0.46	0.62	.01294	*
Verbs	0.56	0.39	0.31	.15604		0.70	0.39	0.39	.07153	
1st Person Pronouns	-0.41	0.36	-0.23	.25388		0.13	0.30	0.07	.66063	

Table 6. Results of the Logistic Regression Predicting Dynamic Representational Gestures

	Study 1					Study 2				
Model 1: Main Effects										
Variables	**β**	**SE**	***d***	**p**		**β**	**SE**	***d***	**p**	
(Intercept)	-20.86	528.79	-11.52	.9685		-2.29	1.14	-1.27	.0437	*
Expert	1.75	0.76	0.97	.0212	*	0.57	0.97	0.31	.5604	
Spatial	-0.05	0.16	-0.03	.7358		0.37	0.22	0.20	.0835	
Native Speaker	0.19	0.82	0.10	.8208		0.48	0.66	0.27	.4944	
Definition/diagram click	18.88	528.79	10.43	.9715		-0.26	0.79	-0.14	.7436	
3D Conjecture	0.44	0.61	0.24	.4737		0.67	0.59	0.37	.2527	
Models 2: Main Effects with Speech										

(Intercept)	-21.32	4036.32	-11.78	.9958	-2.40	1.22	-1.33	.0490	*
Expert	1.85	0.95	1.02	.0512	0.37	1.04	0.20	.7248	
Spatial	0.06	0.20	0.03	.7562	0.43	0.24	0.24	.0768	
Native Speaker	-0.12	0.87	-0.07	.8897	0.47	0.68	0.26	.4900	
Definition/diagram click	19.16	4036.32	10.59	.9962	-0.14	0.83	-0.08	.8668	
3D Conjecture	0.45	0.63	0.25	.4752	0.66	0.59	0.36	.2638	
SMINTEr	-0.36	0.38	-0.20	.3512	0.28	0.31	0.15	.3661	
Verbs	0.58	0.47	0.32	.2132	-0.21	0.35	-0.12	.5400	
1st Person Pronouns	-0.40	0.40	-0.22	.3243	-0.06	0.31	-0.03	.8584	

Table 7. Results of the Logistic Regression Predicting Non-dynamic Representational Gestures

	Study 1				**Study 2**				
Model 1: Main Effects									
Variables	***β***	**SE**	***d***	**p**	***β***	**SE**	***d***	**p**	
(Intercept)	-0.43	0.83	-0.24	.606	-0.18	0.94	-0.10	.8523	
Expert	-0.01	0.58	-0.01	.987	1.19	0.79	0.66	.1343	
Spatial	0.02	0.12	0.01	.892	-0.33	0.15	-0.18	.0239	*
Native Speaker	0.15	0.67	0.08	.821	0.03	0.61	0.02	.9546	
Definition/diagram click	0.34	0.59	0.19	.566	-0.08	0.65	-0.04	.9070	
3D Conjecture	-0.01	0.44	-0.01	.985	-0.81	0.46	-0.45	.0824	
Models 2: Main Effects with Speech									
(Intercept)	-0.36	0.86	-0.20	.676	-0.50	0.98	-0.28	.6085	
Expert	-0.05	0.68	-0.03	.937	1.59	0.86	0.88	.0686	
Spatial	0.01	0.14	0.01	.919	-0.39	0.16	-0.22	.0162	*
Native Speaker	0.08	0.69	0.04	.903	0.21	0.64	0.12	.7446	
Definition/diagram lick	0.34	0.61	0.19	.574	-0.04	0.67	-0.02	.9475	
3D Conjecture	-0.01	0.45	-0.01	.983	-0.85	0.48	-0.47	.0750	
SMINTEr	0.17	0.26	0.09	.983	0.50	0.27	0.28	.0697	
Verbs	0.04	0.30	0.02	.899	0.41	0.28	0.23	.1380	
1st Person Pronouns	-0.25	0.28	-0.14	.374	0.10	0.26	0.06	.6983	