Gesture-Speech Mismatch Predicts Who Will Learn to Solve an Organic Chemistry Problem

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When child learners explain their problem-solving strategies, they often spontaneously produce hand gestures as well. Just as their spoken explanation can be transcribed and coded according to which problem-solving strategies were expressed, spontaneous gestures communicate information that can be coded according to problem solving strategies. That is, researchers have created coding systems that can segment co-speech gesture streams and categorize the gestures according to which problem-solving strategies they express for a variety of problems encountered by child learners, for the purpose of studying the role of gesture in learning. This coding is done independently from speech coding (i.e., with the sound off), and coding systems become more nuanced, are disseminated to multiple coders, and develop better inter-coder reliability over time (e.g., Church & Goldin-Meadow, 1986; Perry, Church & Goldin-Meadow, 1988; Cook, Mitchell & Goldin-Meadow, 2008; Ping & Goldin-Meadow, 2008).

At times, gesture can convey information that adds little to the information conveyed in the accompanying speech. However, at other times gesture conveys information that is different from, or additional to, the information conveyed in speech. Take, for example, a child asked to explain his responses to a Piagetian conservation task. The child is shown two identical tall, thin glasses and is first asked to confirm that each glass contains the same amount of water. While the child watches, water from one of the glasses is poured into a short, wide dish. A child who is not yet able to conserve quantity judges the original glass to have a different amount of water than the dish and justifies the decision by saying, “It’s different because this one’s taller than that one,” while using gesture to indicate the level of the water in the glass. His gesture and speech both focus on height; gesture does not add any information to speech (gesture-speech match). In contrast, consider a child who produces the same comparison of height strategy in speech, but makes a C-shape gesture indicating the glass’s width. This child has conveyed different information in gesture (width information) than in speech (height information) and thus has produced a gesture-speech mismatch (Church & Goldin-Meadow, 1986).

The interesting implication of gesture-speech mismatches from the point of view of learning is that children who produce gesture-speech mismatches on the conservation task prior to instruction are more likely to profit from instruction than children who produce only gesture-speech matches or no gesture at all (Church & Goldin-Meadow, 1986). The same phenomenon has been replicated with older children on a mathematical equivalence task (Perry et al., 1988) and a balance beam task (Pine, Lufkin & Messner, 2004). Gesture-speech mismatch thus appears to index readiness-to-learn in a variety of tasks in young learners.

Here we use organic chemistry to explore gestures’ role in adult learning. We chose this task because learning how to transform and compare molecules in three-dimensional space lends itself particularly well to imagistic strategies, particularly for novices (Stieff, 2007). We asked 43 adult chemistry novices to draw the stereoisomers of a series of six molecules and to explain how they arrived at their answers (pretest). Then, all 43 participants received the exact same instruction, which involved a spoken explanation of diagrams of stereoisomer pairs in different orientations. In the posttest, participants solved a second set of stereoisomer problems and explained their answers (posttest). We asked whether a) adult learners gestured spontaneously at pretest while explaining their problem-solving strategies; b) these gestured and spoken strategies could be reliably coded according to strategy (each independently of the other); c) adults' performance after instruction (at posttest) could be predicted on the basis of the relationship between the spoken and gestured strategies they expressed during pretest explanations.

Do adult learners spontaneously gesture about stereoisomer task at pretest?

We suggest that hand gestures will be ubiquitous in the early stages of learning the concept of stereochemistry. Organic chemistry students often use the imagistic strategy of mental rotation when determining whether two molecules are enantiomers of each other. Students continue to use this mental rotation (MR) strategy even after they become aware of an alternative analytic heuristic (Stieff, 2007). Chemistry experts, however, sometimes employ imagistic strategies but usually use the analytic heuristic or combine imagistic and heuristic strategies when determining a molecule's enantiomers (Stieff & Raje, 2010). In tasks that are strictly MR, both children and adults spontaneously gesture—children when explaining their answers (Ehrlich, Goldin-Meadow & Levine, 2005), and adults when solving difficult problems (Chu & Kita, 2011). Moreover, children and adults who are encouraged to gesture while solving MR problems perform better than those who are not (Zinchenko, et al., 2009; Chu & Kita, 2011). Gesturing about rotation, with or without speech, helps support the spatial work necessary to mentally rotate objects.

Given the link between MR and molecule visualization in the novice learner, we hypothesized that learners will gesture *spontaneously* when explaining how they solved pretest problems. Indeed, gesture was produced along with learners' spoken explanations on 248 out of the 258 explanations during pretest—in other words, subjects only kept their hands still on 4 percent of pretest explanations. Note that gesture was never mentioned in the study, and was not employed by the experimenter, save for disambiguating static deictic points during the introduction and instruction.

Can spoken and gestured problem-solving explanations be categorized and coded?

Research with children has produced reliable coding systems for categorizing the problem-solving strategies learners express in their speech and gesture for a variety of problems. Developing a reliable coding system for even simple problems like Piagetian conservation (Church & Goldin-Meadow, 1986) or mathematical equivalence (Perry et al., 1988) is no small task. We followed a similar process to develop the coding system for identifying spoken and gestured problem-solving strategies produced by the learners in our study. In this exploratory phase, spoken and gestured explanations from the pretest and posttest were transcribed separately, each without attending to the other. A transcription dictionary specific to coding gesture about stereoisomers was developed during this phase as well. After these transcriptions were completed, attempts to identify regularities across responses began. This process requires a series of intensive working meetings between multiple coders who independently use the same manual to code the same videos, then come together to refine and better explicate the coding manual. Over coding iterations, the problem-solving strategies that were most often expressed in gesture and speech were operationalized. It is important to note that the coding system arises from the data—from systematically identifying correct and incorrect responses and parts of incorrect and correct responses spontaneously produced by learners themselves.

The coding categories are described in some detail in Appendix 1. Incorrect strategies typically reveal misunderstandings about the laws of chemistry, misunderstandings about the relationships between 2D models of molecules and molecules that exist in actual 3D space, or misunderstandings about 3D rotation of a complex, dynamic object like a molecule. Correct strategies involve manipulating the spatial arrangement of two substituents attached to a chiral center (in the YZ plane or the XY plane), rotation of the entire molecule for inspection, and so on. The most complete correct strategy (Level 4 in Appendix 1) can be best explained with an illustrative example (see Figure 1). Each of the *Switch on YZ Plane* and *Rotation* strategies count as lower-level "correct" strategies, but a learner must produce all three of these together to have a completely correct Level 4 spoken or gestured explanation.

With a working coding system in place, one coder coded spoken transcripts for problem solving strategies expressed for each pretest and posttest trial. She then coded gestured transcripts for each pretest and posttest trial, while also watching the video (but not audio). Finally, participants' drawings were coded for each pretest and posttest trial—either 1 (participant drew a correct stereoisomer, or correctly stated that a given molecule does not have a stereoisomer form when it actually does not) or 0 (incorrect drawing, or incorrectly stated a given molecule does not have a stereoisomer form when it actually does). Reliability was assessed by having a second, independent transcriber code 10% of the 516 pretest and posttest trials (43 subjects, 6 pretest and 6 posttest trials each). Agreement between the two coders was 98% for identifying a correct drawing, 91% for coding speech strategies, and 82% for coding gesture strategies[1]. The number of pretest trials that could be coded according to our coding scheme are shown in Table 1.

We also found that learners often expressed multiple problem solving strategies in both speech and gesture during pretest trials. On average, participants expressed 1.2 strategies in speech and 1.4 in gesture per trial on the pretest; 49 of the 258 pretest trials contained more than one strategy in speech; 53 contained more than one strategy in gesture. The distribution of strategies on the pretest was roughly comparable in speech and gesture (Table 1). For example, the Level 2 *Switch on 1 Plane (either X-Y or Y-Z)* strategy was the most common strategy produced in both speech and gesture on the pretest, and the completely correct Level 4 strategy was rare in both. The one exception was the Level 2 *Rotate* strategy, which was found in .25 of the pretest gesture strategies but only .14 of the pretest speech strategies, suggesting that participants may have had a greater understanding of rotation than their speech revealed.

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[1] It is also worth noting that the same coding system is still in place, and is still being refined and the coding manuals better explicated. The researchers who are currently working with the coding manual were not involved in its creation, and have established independent reliability with one another using the speech coding manual. Similar reliability work is ongoing with the gesture coding manual.

Overall, not only did the learners in our study gesture, but their gesture embodied codable problem solving strategies. This raises the possibility that attending to learners' gestures—not just their speech—could provide a more complete picture of what they know.

Did learners produce gesture-speech mismatch at pretest? Does it predict readiness to learn?

Adults have been found to produce gesture-speech mismatches on a range of tasks, for example: reasoning about moral dilemmas (Church et al., 1995), explaining solutions to the Tower of Hanoi puzzle (Garber & Goldin-Meadow, 2002) and how gears work (Perry & Elder, 1997), describing pictures of landscapes, abstract art, buildings, people, and machines (Morrel-Samuels & Krauss, 1992), describing solutions to problems involving constant change (Alibali et al., 1999), and narrating cartoon stories (Beattie & Shovelton, 1999; McNeill, 1992; Rauscher, Krauss, & Chen, 1996). But we do not yet know whether these mismatches signal the adults' openness to instruction on tasks. We ask here whether a) the adult learners in our study produced gesture-speech mismatches; b) the mismatch between gesture and speech reveals openness-to-instruction not only for children learning relatively simple tasks, but also for novice adults learning sophisticated scientific concepts.

We compared the strategies produced in speech and in gesture on each pretest trial and classified trials into one of 5 groups: (1) speech conveys strategies with no accompanying gesture; (2) gesture conveys strategies also conveyed in the accompanying speech; (3) gesture conveys at least one incorrect strategy (levels 0 or 1) not conveyed in the accompanying speech (see Figure 2a for one example); (4) gesture conveys at least one correct or partially correct strategy (levels 2, 3, or 4) not conveyed in the accompanying speech (see Figure 2b for one example); (5) gesture conveys at least one incorrect strategy and one correct strategy not conveyed in the accompanying speech. Table 2 presents the number of trials of each type that participants produced on the pretest.

We then classified *learners* into 4 groups based on the strategies they expressed on the pretest: (1) Matchers: participants who always produced gestures that conveyed the same information as their speech; i.e., their gestural responses added no new information to the information they conveyed in speech (N=4). (2) Incorrect Mismatchers: participants who produced at least one gestural response that added only incorrect information to the information they conveyed in speech (N=7). (3) Correct Mismatchers: participants who produced at least one gestural responses that added only correct information to the information they conveyed in speech (N=18). (4) Correct/Incorrect Mismatchers: participants who produced at least one gestural response that added correct information and one that added incorrect information to the information conveyed in speech (N=14). Within each of these categories, the speech expressed strategies at varying levels of correctness; importantly, there were no differences in the mean strategy level of the responses that these 4 groups expressed in *speech* on the pretest (see Table 3), $F(3, 40)=0.023$, *ns.* Approximately the same proportion of adults in each group expressed incorrect strategies (i.e., Levels 0 or 1) in speech on the pretest (0.75, 1.00, 0.78, 0.86, respectively). In other words, the groups differed only in the relation between their speech and their gestures.

Spoken and gestured responses on the posttest questions were coded as in the pretest. To receive credit for having solved a problem correctly, a participant had to create a correct drawing, and provide a completely correct Level 4 response in speech (see Figure 1 speech). Using this criterion, we found that none of the 11 participants in either the first or the second groups (Matchers or Incorrect Mismatchers) produced any correct responses on the posttest. In contrast, 5 of the 18 (.28) participants in the third group (Correct Mismatchers) and 4 of the 14 (.29) participants in the fourth group (Correct/Incorrect Mismatchers) produced at least one correct response on the posttest (see Table 3).

Thus, gesture-speech mismatch *per se* did not predict learning—only participants whose mismatches contained gestures that added *correct* information (on its own or with incorrect information) to the information conveyed in speech improved after the instruction. Participants whose mismatches contained gestures that added *only incorrect* information to the information conveyed in speech showed no more improvement than participants whose matching gestures conveyed the same information as their speech. In other words, adults whose gestures conveyed correct information not found in their speech were significantly more likely to make progress on the posttest (9 out of 32) than were adults whose gestures either matched their speech or conveyed only incorrect information not found in their speech (0 out of 11), Fisher Exact Test, $p = .05$. Note, however, that only 28% of the participants who produced correct mismatches made progress on the posttest and their progress was minimal—on average, the 9 participants solved only 1.44 problems (out of 6) correctly on the posttest.

Conclusion

The learners in our study spontaneously gestured during nearly every spoken pretest explanation. We were able to create a coding manual to capture the problem-solving strategies expressed in both gesture and speech. We also found that most of the adults in our study produced at least one problem-solving explanation in their gesture that was additional to that expressed in speech. Further, adults whose gesture added *correct* problem-solving strategies to those expressed in speech were the only adults who profited from instruction on the task.

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Table 1. Distribution of speech and gesture strategies produced on the pretest [a.]

Level	Strategy	Strategies in Speech (N=256)	Strategies in Gesture (N=208)
Incorrect Strategies			
0	*Changes are Either Not Possible or Irrelevant*	.05	.01
	Changed Bond Length or Angle Size	.01	.07
1	*Ignoring the Y-Z plane*	.20	.10
	Impossible or Irrelevant use of the Y-Z plane	.10	.03
	Impossible of Irrelevant Rotation	.07	.10
Partially Correct Strategies			
2	*Switch on 1 Plane (either X-Y or Y-Z)*	.25	.29
	Rotation	.14	.25
3	*Mirror Image*	.07	.01
	Toward & Away	.09	.13
Fully Correct Strategies			
4	*Compare the Non-Manipulated Substituents*	.02	.01

a. Participants produced no gestures on 10 pretest trials. In addition, 29 of the strategies produced in speech on the pretest and 77 of the strategies produced in gesture could not be coded into one of the categories.

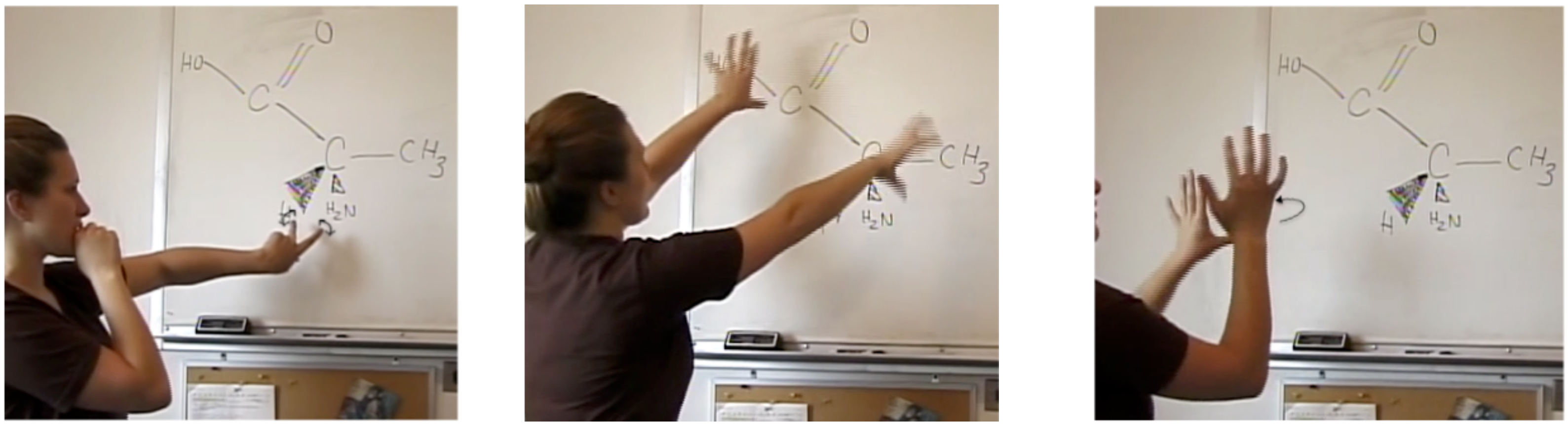
Table 2. Number of trials on the pretest classified according to the relation between strategies conveyed in speech and gesture

Type of Trial Classified According to the Relation between Speech and Gesture	Total Number of Trials (N=258)	Proportion of Total Trials
Speech is not accompanied by gesture	10	0.04
Gesture conveys strategies also conveyed in the accompanying speech	155	0.60
Gesture conveys at least 1 incorrect strategy (level 0 or 1) not conveyed in the accompanying speech	29	0.11
Gesture conveys at least 1 correct strategy (levels 2, 3, or 4) not conveyed in the accompanying speech	60	0.23
Gesture conveys at least 1 incorrect and 1 correct strategy not conveyed in the accompanying speech	4	0.02

Table 3. Pretest speech levels and posttest performance of participants classified according to the relation between speech and gesture on their pretest responses

Participants Classified According to the Relation between Speech and Gesture on the Pretest	Mean Speech Level at Pretest	Number of Participants Who Produced at least 1 Correct Response on the Posttest
Matchers N=4	1.72 (SD=.74)	0
Incorrect Mismatchers N=7	1.79 (SD=.35)	0
Correct Mismatchers N=18	1.73 (SD=.55)	5
Correct/Incorrect Mismatchers N=14	1.75 (SD=.47)	4

Figure. 1. An example of a Level 4 strategy in speech and in gesture.



Switch on 1 (Y-Z) Plane	*Compare the Non-Manipulated Substituents*	*Rotation*
"Well I reversed the spatial arrangement of these two, so now you can't like…	…Since these are not the same on either side of the main carbon,	then you can't like flip it at all."
Index and middle finger each point at one substituent on the Y-Z plane, and wiggle back and forth.	Left hand flat—points at one substituent on the X-Y plane; right hand flat—points at the other substituent on the X-Y plane.	Both hands mimic rotation in front of the molecule.

Figure 2. Examples of an Incorrect (a) and a Correct (b) Mismatch. The problem-solving strategy conveyed in speech is identical in the two examples; the only difference is that the information conveyed in gesture is incorrect in (a) and correct in (b).

(a) Incorrect Mismatch

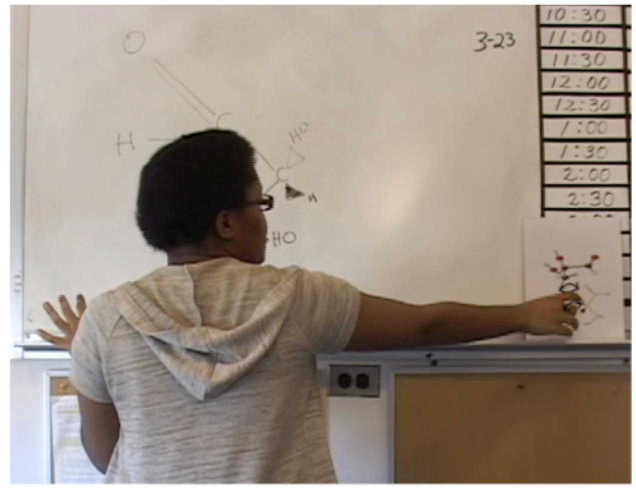
Gesture: *Irrelevant Rotation*

Points at non-manipulated substituents and does a rotate gesture in front of them

Speech: *Rotate*

“All I did was flip the molecule up the other way around.”

(b) Correct Mismatch



Gesture: *Switch on Y-Z Plane*

Two fingers each point to the substituents on the Y-Z plane and then wiggle back and forth

Speech: *Rotate*

“But I just took the way it’s drawn here and I flipped it over.”

Level	Strategy	Description	Speech	Gesture
Incorrect Strategies				
Level 0	Changed Bond Length or Angle Size	Participants indicate that by changing the length of the bonds between atoms or altering the angle between two bonds, they have created a stereoisomer.	"I made the bonds between the carbon and the hydrogen shorter"	Participants pinch two fingers together over the C and H.
	Changes are Either Not Possible or Irrelevant	Participants indicate that regardless of how they change the molecule it can always be rotated back to the original form and thus cannot create a stereoisomer. Alternatively, they indicate that due to the laws of chemistry no changes are allowed to be made.	"Anyway I drew it, it would still be superimposable on the original molecule"	Participants point or sweep to every substituent and produce no other gestures.
Level 1	Ignoring the Y-Z Plane	Participants indicate having changed the location of two substituents on the Y-Z plane by altering their spatial relation on the X-Y plane.	"Originally the hydrogen and the hydroxide were both on the left side of the carbon. Now the hydrogen and the hydroxide are both on the right side of the carbon."	Participants sweep from one substituent to the left or right side of another substituent that has been 2-dimensionally changed.
	Impossible or Irrelevant use of the Y-Z Plane	Participants indicate that by changing the 3-dimensional position of substituents that are NOT attached to the chiral center they have created a stereoisomer. Alternatively, they have manipulated the spatial	"I changed the molecule so everything is now in the same plane."	Participants point to (or position their hand directly in front of) a substituent that is not attached to a chiral center, and then sweeps away from or toward the board or both.

		locations of irrelevant parts of the molecule.		
	Impossible or Irrelevant Rotation	Participants indicate that rotating two or more substituents that are NOT attached to the chiral center will produce a stereoisomer.	"I rotated all of the hydrogen atoms around the carbon so now it is different"	Participants lift up one hand with fingers pointed upward (or both hands) and twist the hand(s) either clockwise or counter-clockwise. The movement is produced in front of a substituent not attached to a chiral center.
Partially Correct Strategies				
Level 2	Switch on 1 Plane (either X-Y or Y-Z)	Participants indicate that by switching the positions of two substituent groups either on the X-Y plane or on the Y-Z plane, they have created a stereoisomer. The switched substituents must both remain on the same plane. On the X-Y plane: Two substituent groups attached to the chiral center have switched places. OR On the Y-Z plane: Two substituent groups attached to the chiral center have changed their orientations so that one is now pointed toward the participant and the other is pointed away.	"It is not superimposable because I switched the orientation of the chlorine and the hydrogen." OR "Now the chlorine is coming out, towards the observer, and the hydrogen is going away from you. On the original the chlorine is going away from the observer, and the hydrogen is coming toward you so this wouldn't be superimposable."	Participants point with an index finger or a V-shaped hand to two substituents attached to a chiral center and flipped or reversed the hand. OR Participants point to (or position their hand directly in front of) a substituent that is attached to a chiral center and then sweep away from or toward the board or both.
	Rotation	Participants indicate that no matter how their drawn molecule is rotated, it cannot be superimposed on the	"Because regardless of how you rotate the molecule, it can't be superimposed on the original."	Participants lift up one hand with fingers pointed upward (or both hands) and twist the hand(s) either

		original molecule. For items that do not have a stereoisomer, rotating the drawn molecule will return the arrangement to its original form and thus it can be superimposed on the stimulus.		clockwise or counter-clockwise. The movement is produced in front of a substituent attached to a chiral center or in front of the entire molecule.
Level 3	Mirror Image	Participants indicate that by creating the original molecule's mirror image they have created a stereoisomer.	"If you reflect the molecule over a mirror plane then you couldn't match it up with the original."	Participants place one hand over one drawing and then flip their hand from palm down to palm up over the top of either the stimulus or an empty space next to their drawing.
	Toward & Away	The two Level 2 strategies produced in combination: Switch on 1-plane and Rotation.		
Fully Correct Strategies				
Level 4	Compare the Non-Manipulated Substituents	Participants indicate that after having manipulated the molecule using either Mirror Image (Lv. 3) or Toward & Away (Lv. 3), they rotated the molecule so that the manipulated substituents lined up with their original orientations. They then compared the two non-manipulated substituents' locations to their original orientations.	"When you change which one of these two groups are going into the board and which one is coming out of the board, no matter how you rotate the molecule, it won't be the same as the original because the two groups that you didn't manipulate won't line up with their original places."	After producing the required lower level gestures, participants then must point to one or both of the remaining substituents attached to the chiral center.