Gestures for Thinking

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Abstract

Can our gestures help us think, and, if so, how? Previous work suggests that they can. Here, students, alone in a room, studied descriptions of environments for later tests of knowledge. The majority of participants spontaneously gestured while reading the descriptions, and most of those also gestured while answering true-false questions. They did not gesture proportionately more time for environments with many landmarks than for environments with few. Their gestures laid out the environments, primarily using points to places and lines for paths. Descriptions and questions accompanied by gestures were remembered more accurately. Participants rarely looked at their hands. Gestures seem to promote learning by establishing embodied representations of the environments.

Keywords: Gesture; embodiment; spatial representation; spatial memory; route/survey perspectives; navigation.

Introduction

Gestures serve many ends and have many forms. People gesture in communications to others, but also for themselves, that is, they gesture to think (Goldin-Meadow, 2003; McNeill, 1992). Gestures for thinking help thinking in different ways. They help people find words (Krauss & Hadar, 2001). They offload memory (Cook, Yip, & Goldin-Meadow, 2012; Goldin-Meadow, Nusbaum, Kelly, & Wagner, 2001). They help people perform mental rotation (Chu & Kita, 2008; Wexler, Kosslyn, & Berthoz, 1998; Wohlschlager & Wohlschlager 1998). They help people count (Carlson, Avraamides, Cary, & Strasberg, 2007).

Gestures are actions in space, and as such, can readily represent spatial structures and spatial actions. In fact, gestures help people solve spatial problems (Kessell & Tversky, 2006; Schwartz & Black, 1996). Interestingly, in solving spatial problems, gestures can serve much like diagrams. When given paper and pencil during problem solving, one group diagrammed the same spatial problems that another group gestured to solve (Kessell & Tversky, 2006). Diagrams also offload memory, but they serve cognition in many other ways. Creating a good diagram entails extracting the crucial information and structuring it to represent a problem to be solved or information to be comprehended and learned felicitously, yielding an integrated external model of the information that can be inspected and mentally manipulated (e. g., Tversky, 2011). Gestures are crude, and as such almost necessarily abstract. They can also create integrated external models. In explaining complex environments or scientific systems, people produced a coordinated and integrated series of gestures that modeled the spaces of environment (Emmorey, Tversky, and Taylor, 2000), family trees (Enfield, 2003), and scientific processes (Kang, Tversky, and Black, 2013) to be learned.

People gesture to explain spatial environments to others, creating external models with their hands. Will they do so for themselves, as aids to comprehension and memory? Here, we investigate whether people, alone in a room studying descriptions of complex environments will gesture for themselves. If so, what is the nature of their gestures? And does gesturing help them learn and remember the environments?

Gesturing could help learning and memory indirectly by off-loading memory to another modality. Gestures have been shown to be effective in off-loading memory during explanations (Goldin-Meadow, et al, 2001). But gestures could also help learning and memory in direct ways, by constructing an external model of the environment to be learned. Half the environments participants studied had 4 landmarks and half had 8 landmarks; the latter should put greater stress on working memory (e. g., Jonides, Lewis, Nee, Lustig, Berman, and Moore, 2008). If the primary role of gestures is to offload working memory, participants should gesture more when studying descriptions with more landmarks. If the primary role of gestures is to construct a model of the environment, much like a diagram, then there is little reason to expect more gesturing for the environments with more landmarks. Gestures can reflect mental representations (e. g., Alibali, Bassok, Olseth, Syc, and Goldin-Meadow, 1999). Description perspective was manipulated because route and survey descriptions yield different mental representations early (but not late) in learning (Lee and Tversky, 2005).

Method

Participants. 48 (28 female, 20 male), primarily graduate students from Columbia University, were paid to participate in the study. Participants were native English speakers or have graduated from an English speaking high school.

Descriptions. The environments had 4 or 8 landmarks. There were three outdoor environments, Etna City, Chinatown, and the Financial district, and three indoor environments, a spa, an electronics show, and a grocery store. There were 8 landmarks and 4 landmarks versions of each of these.

There were also versions of each environment from route (R) or survey (S) perspectives. A route perspective takes an imaginary traveler, you, through an environment describing the turns and landmarks with respect to "you" in terms of your left, right, front, and back. A survey perspective takes an overview of an environment and describes landmarks with respect to each other in terms of north-south-east-west. The route descriptions always began with cardinal directions so that participants could answer questions from a survey perspective. The descriptions and the environments were based on earlier work (Taylor & Tversky, 1992).

The average length of the 8R descriptions was 141 words, of the 8S descriptions, 127 words, of the 4R descriptions, 69 words, and of the 4S descriptions, 72 words. Table 1 shows an example of a description of an outdoor environment with 4 landmarks from a survey perspective, and of an indoor environment with 8 landmarks from a route perspective.

Table 1: Examples of descriptions

Example 1: 4S outdoor environment Etna is a charming town nestled in an attractive valley, entered on River Highway. River Highway runs east-west at the southern edge of the town of Etna. Toward the eastern border, River Highway intersects with Mountain Rd, which runs north of it. At the northwest corner of the intersection is a gas station. North of the gas station, Mountain Road will intersect with Maple Ave, which runs west.
Example 2: 8R indoor environment Rock Creek Center is a showcase for new electronic devices. Enter Rock Creek Center from the east side of the building near the southeast corner. As you enter, you see, on the left wall, a Bulletin Board. Past the Bulletin Board, on your right is the Video Camera room and on your left is the Office stretching to the corner of the building. Past the office you are forced to turn right and you will find the Cafeteria on your left stretching to the corner of the building. After the Cafeteria, you are forced to turn right and you will find a large room with Mobile Phones on your left. On your right you will see the Televisions room. At the end of the hallway, turn right and you will find the Laptop Center on your left. Past the Laptop Center, you will return to the entrance on your left.

Design. Each participant read four descriptions, one with 4 landmarks and one with 8 landmarks from each perspective. The specific environment for each condition was chosen from the set of three outdoor environments and three indoor environments. All variables, size, perspective, environment, order were counter-balanced and appeared equally often across participants.

True-false Questions. Verbatim and inference statements were designed for each description, 10 for the 8 landmark environments and 6 for the 4 landmark environments. For the 8 landmark environments, there were 2 statements taken verbatim from the text with the same perspective, 2 statements taken verbatim from the text with the other perspective, and 6 inference statements, 3 route, and 3 survey. For the 4 landmark environments, there were a total of 6 statements: 1 verbatim from the route perspective, 1 verbatim from the survey perspective, 2 inference from a route perspective, and 2 inference from a survey perspective. Inference statements could be verified from information provided in the descriptions. Half of the statements were true and the other half was false. The statements were presented in a random order for each participant. Table 2 shows examples of true/false statements for Etna.

Table 2: Examples of true/false statements

	Verbatim	Inference
Route	Going east on River Highway, at the intersection with Mountain Rd, you will find a gas station on your left.	From Mountain Rd, turn right on River Highway and you will have the Gas Station on your right.
Survey	North of the gas station, Mountain Road will intersect with Maple Ave, which runs east.	South of Maple Ave to the west of Mountain Rd is the Gas Station.

Procedure. Participants first signed a consent form, assenting to participating in the experiment and to being videotaped. They were additionally asked for permission to show their videos in presentations of the research. They then completed a paper version of the Mental Rotation Task (Vandenberg & Kuse, 1978), a common test of spatial ability.

Participants were seated in front of a Mac OS X 10.7, as shown in Figure 1. Video records of the computer screen and front views of participants were captured with *Silverback©* software, and participants' side views with a videocam. The experimenter explained the procedure to each participant: "In this study you will be asked to read 4 text descriptions of environments. After reading each description, your memory for the information in the text will be tested. You will start with a practice text description. Throughout the study, you will not have access to a keyboard and will send commands to the computer with your voice." The participants responded verbally, saying "next", "yes", or "no" when appropriate, to advance from screen to screen. Their responses were analyzed by the Mac speech recognition program and used to advance screens and record responses. This left participants' hands free to gesture, on or off the table.

Participants first had a practice trial. The first screen explained the task: "You will be asked to read the description of an environment as practice. Once you are done reading the description say aloud "Next". After the description you will be asked to judge the truth of some statements about the environment. You may take as much as time you need." Then participants read a description of an amusement park. The complete description was on the screen. Participants were free to read the practice and experimental descriptions as long as they liked. Immediately after reading the description, participants were presented with 4 true/false questions, one on each screen. They said "yes" for true and "no" for false. After the practice trial, the experimenter answered any questions the participant had, and then left the room.

Participants then proceeded through the experiment, reading each of the four descriptions and answering the corresponding true/false questions after each.

Figure 1: Experimental Setup. Participant gesturing while studying description.

Results

Coding. Two trained coders, coded 10 of 48 videos for gesturing while studying, Kappa = 0.76 ($p < 0.001$), for length of time spent gesturing while studying, t(39)= 0.244, p= 0.809, for looking at their hands while gesturing while studying, Kappa = 0.56 ($p < 0.001$), for studying time, t(39)= 1.402, p= 0.169, for gesturing while verifying statements, Kappa = 0.90 ($p < 0.001$), for looking at their hands while gesturing in verifying statements, Kappa = 0.44 ($p < 0.001$), and for length of time to verify statements, t(359)= 0.120, p= 0.90. Any movement of hands or fingers, excluding beat gestures, was coded as gesturing. Any glance at hands while gesturing was coded as looking. The coded duration of the gesture included active movements and periods when individuals left their hands still on the table or in mid-air in a certain position and form. Times were coded from the *Silverback©* videos of the screen and by using ELAN software. In cases of disagreement coders consulted a third coder. One coder coded the remaining videos, discussing uncertain cases with the second coder. Qualitative coding of the gestures is ongoing, but it is clear that gestures indicating places, primarily points, and indicating connections between places, drawing lines or placing the edge of a hand, predominate. Most gestures were performed on the table, but some were in the air (see Figures 1 and 2).

Gesture at study. Seventy-three percent of participants (35 out of 48) gestured at least once for at least one description during study. Twelve participants (25%) gestured for all four descriptions, 7 gestured for three, 10 gestured for two, and 6 for only one. Notably, number of landmarks in the environments (4 vs. 8) did not influence whether participants gestured at study, $\chi^2(1, N= 48)= 1.132$, p= 0.289. Similarly, neither perspective (route vs. survey), $\chi^2(1, N= 48)= .023$, p= 0.879, order (1st, 2nd, 3rd, or 4th), $\chi^2(3, N= 48)= 1.687$, p= 0.171, or MRT score , F (1, 185)= 0.089, p= 0.765, influenced gesturing at study.

For each participant, the percentage of time gesturing while studying was computed. Neither spatial ability F(1, 45)= 0.357, p= 0.553) nor gender (F(1, 45)= 0.505, p= 0.481) affected the percent of time gesturing

Gesture at test. Sixty-five percent of participants (31 out of 48) gestured at least once when verifying the true/false statements. Table 3 shows number of statements for which participants gestured both when studying and answering, only when studying, only when answering, or not at all, out of the total of 1526 statements (excluding 10 cases in which participants' answers were missing).

Figure 2. Participant gesturing while answering question.

Table 3: Number of questions and gesture behavior

Gesturing	Frequency	Percentage
Both at study and when verifying	547	35.8%
Only at study	220	14.4%
Only when verifying	21	1.4%
None	738	48.4%

As evident from Table 3, participants were far more likely to gesture to verify statements for the descriptions they gestured at study. Only 1.4% of the questions received gestures at verification that had not received gestures at study.

Moreover, for 85% of the descriptions accompanied by gesture, at least one question was also accompanied by gesture. Participants, who did not gesture at all while studying the descriptions did not gesture when answering questions. Specifically, 27% of participants (13 out of 48) did not gesture either at study or at verification.

Overall, neither the environment's perspective (survey vs. route), $\chi^2(1, N= 48)= .743$, $p= 0.389$, nor question perspective, $\chi^2(1, N= 48)= .264$, $p= 0.608$, nor number of landmarks (4 vs. 8), $\chi^2(1, N= 48)= .028$, $p= 0.868$, nor type of statement (verbatim vs. inference), $\chi^2(1, N= 48) = .439$, $p= 0.508$, nor MRT scores, $F(1, 1520) = 0.899$, $p= 0.343$ influenced whether participants gestured at verification.

In short, most participants gestured while studying and verifying and most who gestured at verification had also gestured at study. Neither spatial ability nor length nor perspective of the descriptions or questions affected whether participants gestured.

Accuracy. As evident in Figure 3, when participants had gestured at study, they were more likely to be accurate at testing (M= 0.821, SD = 0.29) than when they had not gestured at study (M= 0.743, SD = 0.30), $F(1, 1517) = 8.249$, $p=0.004 < 0.01$. Not surprisingly, accuracy was higher for the 4 landmark environments (M= 0.810, SD= 0.24) than for the 8 landmark environments (M= 0.760, SD= 0.28), $F(1, 1517)= 6.561$, $p= 0.011 < 0.05$. Accuracy improved with spatial ability, $F(1, 1517)= 10.210$, $p= 0.001 < 0.01$ but the correlation between accuracy and spatial ability was low and not significant. Accuracy varied with kind of statement, $F(1, 1517)= 7.182$, $p < 0.001$. Replicating Taylor and Tversky (1992), post-hoc analyses showed that verbatim statements (M= 0.838, SD= 0.21) were more accurate than inference statements (M= 0.720, SD= 0.31), $t(1513)= 3.809$, $p < 0.01$, and that for inference statements, there was no advantage for statements in the perspective of reading (same perspective (M = 0.727, SD = 0.30); other perspective (M = 0.718, SD = 0.31), $t(1513) =0.311$, $p= 0.756$), indicating that memory representations were perspective-free.

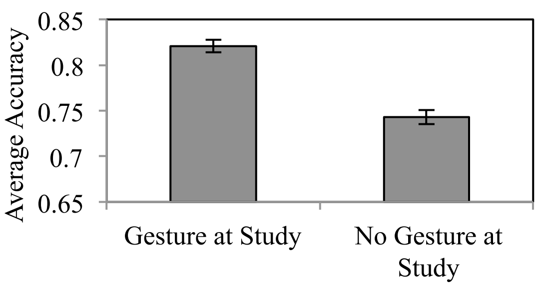

Figure 3. Accuracy by gesturing at study. Error bars represent standard error

The effects of gesturing at verification were analyzed separately. Participants were more likely to be accurate verifying statements when they gestured (M= 0.814, SD= 0.23), than when they did not (M= 0.757, SD= 0.29), $F(1, 1515)= 5.325$, $p= 0.038 < 0.05$. As before, accuracy increased with spatial ability, $F(1, 1515)= 10.191$, $p=0.001 < 0.01$, and was affected by statement category in the same ways as the previous analysis, $F(1, 1515)= 17.084$, $p < 0.001$.

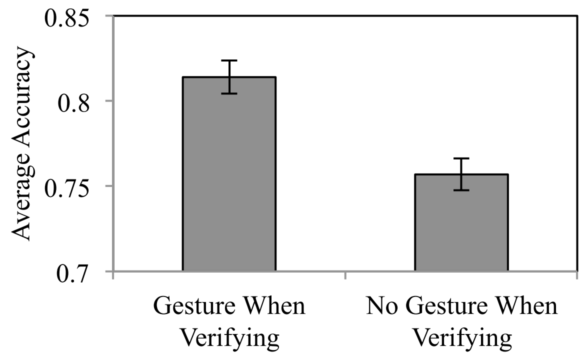

Figure 4: Accuracy by gesturing at verification.

To examine the effects of gesture at study and gesture at response, participants were divided into 4 groups: gesture at both, gesture only at study, gesture only at response, no gesture. Gesture behavior had an effect on accuracy, $F(3, 1494)= 3.593$, $p= 0.013 < 0.05$. Post-hoc analyses showed that participants were more accurate at testing when they had gestured both at study *and* verification (M= 0.780, SD= 0.27), than when they did not gesture at all (M= 0.705, SD= 0.32), $t(1494)= 2.491$, $p= 0.013 < 0.05$. Similarly, they were more accurate when they only gestured at study (M=0.816, SD=0.23), than when they did not gesture at all, $t(1494)= 2.655$, $p= 0.008 < 0.01$. However, there was not a significant improvement for gesture only at response (M= 0.811, SD=0.25) than for no gesture, $t(1494)= 0.333$, $p= 0.739$; this could be due to the severely limited number of cases in which participants only gestured at response (See Table 3).

To make sure that the advantage of gesturing was not because the better learners gestured, comparisons were done within participants who gestured when studying two or three descriptions, but not all descriptions. For those who gestured sometimes, accuracy was higher when they gestured at study (M= 0.762, SD = 0.29) than when they did not (M= 0.677, SD = 0.35), $F(1, 513) = 3.938$, $p= 0.048 < 0.05$. Similarly, they were more accurate verifying statements when they gestured (M= .764, SD= 0.29) than when they did not gesture (M= 0.628, SD= 0.35), $F(1, 513)= 3.910$, $p= 0.049 < 0.05$. So, gesturing itself helps - it is not just that those who tend to gesture also remember better.

Studying Times. As expected, participants took longer to study the longer descriptions with 8 landmarks (M= 112.14sec, SD= 28.43) than the shorter ones with 4 landmarks (M= 56.57sec, SD=28.43), $F(1, 187)= 94.104$, p

< 0.001. Gesturing did not influence study time, $F(1, 187)= 1.212$, $p= 0.272$. Similarly, neither spatial ability, $F(1, 187)= 2.198$, $p= 0.140$, nor text perspective, $F(1, 187)= 0.101$, $p= 0.752$, affected study times.

Verification Times. Figure 5 shows that gesture behavior influenced verification time, $F(3, 1441)= 3.431$, $p= 0.016 < 0.05$. Post-hoc Bonferroni comparisons showed that participants were faster to verify statements when they had only gestured at study (M= 8.95 sec, SD= 2.61) than when they had not gestured at all (M= 10.35 sec, SD= 4.16), $p < 0.001$. By contrast, answering took longer when participants only gestured at verification (M= 15.65 sec, SD= 6.19) than when they only gestured at study, $p=0.004 < 0.01$. There was no difference on verification time when participants gestured both at study *and* at verification (M= 11.47 sec, SD= 3.88), compared to when they did not gesture at all. Spatial ability, perspective, and size of environment did not effect verification times. Thus gesture at study decreased verification time while gesture at responding increased verification time, and in cases when they gestured both at study and at verification, the two effects cancelled each other.

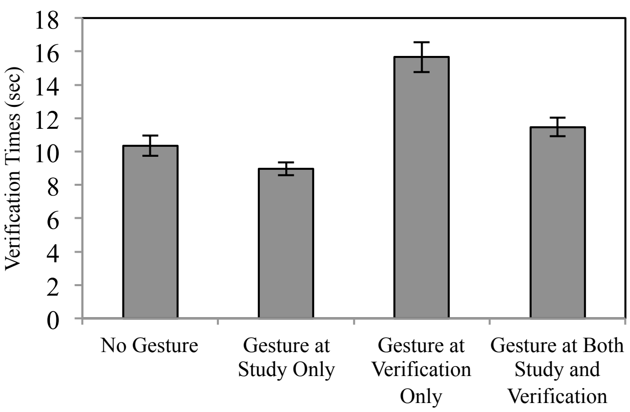

Figure 5: Verification time by gesture behavior

Did participants look at their hands while gesturing? For the most part, participants did not look at their hands while gesturing; they looked at their hands for 35.8% of the texts during reading but they were typically brief glances. Out of the 35 participants who gestured at least once when reading texts, 15 never looked at their hands. At verification, participants looked at their hands for less than 10% of the statements they gestured while verifying. Out of the 31 participants who gestured for at least one of the statements, 16 never looked at their hands.

Discussion

Participants, alone in a room, read descriptions of a variety of complex environments that they were to learn for later questions. While they were studying, most of them gestured at least once, and the majority gestured for most of the descriptions, in the absence of any communication. The descriptions accompanied by gestures were remembered better than those that were not, and the questions that were accompanied by gestures were answered more accurately than those that were not. The advantage of gesturing on memory cannot be explained as the better participants both gestured and remembered better. Even within those participants who frequently gestured, gesturing at study and at responding improved memory. Gestures modeled the structures of the environments, pointing to places and outlining paths between places. Except on rare occasions, participants did not look at their hands as they gestured, suggesting that it is the actions *per se* that serve comprehension and learning, rather than the visual accompaniments. Overall, spontaneous gesturing at learning and spontaneous gesturing at memory retrieval promoted learning. Gestures appeared to improve learning by establishing embodied representations of the structures of the environments and appear to improve memory by redintegrating the queried parts of the environments.

In addition to providing embodied representations of the environments, gestures might also have served to offload memory, as in previous research (e. g., Cook, et al., 2012; Goldin-Meadow, et al., 2001), just as diagrams offload memory. However, the proportion of study time gesturing did not increase as memory load increased from light to heavy. Thus, the role of gesture in lightening memory load appears to be less important for comprehending and learning complex environments than other features of gestures, notably, creating embodied representations.

Gestures are actions, and thereby provide an additional code beyond the verbal code participants read. Multiple codes in multiple modalities are known to promote memory (e. g., Paivio, 1986). Motor codes in particular augment memory (e. g. Engelkamp & Zimmer, 1994; Hommel, Musseler, Aschersleben, & Prinz, 2001) but the cases that have been studied have primarily been cases where the memory was for the action per se. In the present case, the actions served memory not for the actions but rather for what the actions represented.

Actions, like diagrams and words, can represent, that is, they can stand for something other than themselves. Certainly for the case of words but also for the case of diagrams, representation seems to be their primary function. Not so for actions. Actions can represent, but they are primarily used for the ordinary (and extraordinary) tasks of life, manipulating objects and navigating environments. Gestures are a special class of actions that serve to represent rather than to act on or in the world. Similar to diagrams, gestures can represent more directly than purely symbolic words; they bear some resemblance to what they represent (e. g., Tversky, 2011).

Like diagrams, gestures can use space to represent ideas that are spatial or metaphorically spatial (e. g., Enfield, 2003; Emmorey, et al., 2000; Tversky, 2011; Tversky, Heiser, Lee, & Daniel, 2009). Like diagrams, gestures are spatial and visual. However, it seems that the spatial and action components of representational gestures serve comprehension and memory rather than the visual. Participants rarely looked at their hands. Researchers in art, sketching, and design refer to drawing as *gesture*. Blindfolded architects gesture copiously as they design, and they cannot see either their gestures or their designs. Nevertheless, their designs equal those they create without blindfolds (Bilda and Gero, 2006). Together, these findings suggest that some of the benefits of gesturing to those who gesture may be the embodiment of thought into action.

Acknowledgments

The authors are indebted to NSF IIS-0725223, NSF IIS-0855995 and NSF IIS-0905417 for supporting parts of the research and manuscript preparation. Valeria Giardino is grateful to The Italian Academy for Advanced Studies in America at Columbia University for supporting her visit.

References

Alibali, M. W., Bassok, M., Olseth, K. L., Syc, S. E., & Goldin-Meadow, S. (1999). Illuminating mental representations through speech and gesture. *Psychological Science, 10*, 327-333.

Bilda, Z and Gero, J.S. (2006) Reasoning with internal and external representations: A case study with expert architects. In R Sun (ed), *CogSci/ICCS 2006,* Lawrence Erlbaum, pp. 1020- 1026.

Carlson, R. A., Avraamides, M. N., Cary, M., & Strasberg, S. (2007). What do the hands externalize in simple arithmetic? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *33*(4), 747-756.

Chu, M., & Kita, S. (2008). Spontaneous gestures during mental rotation tasks: Insights into the microdevelopment of the motor strategy. *Journal of Experimental Psychology: General, 137,* 706–723.

Cook, S. W., Yip, T. & Goldin-Meadow, S. (2012). Gestures, but not meaningless movements, lighten working memory load when explaining math. *Language and Cognitive Processes*, *27,* 594-610.

Emmorey, K., Tversky, B., & Taylor, H. (2000). Using space to describe space: Perspective in speech, sign, and gesture. *Spatial Cognition and Computation, 2,* 157-180.

Enfield, N. (2003). Producing and editing diagrams using co-speech gesture: Spatializing non-spatial relations in explanations of kinship in Laos. *Journal of Linguistic Anthropology, 13*, 17-50.

Engelkamp, J. and Zimmer, H. D. (1994). *Human memory: A multimodal approach.* Seattle: Hogref and Huber.

Goldin-Meadow, S. (2003). *Hearing gesture: How our hands help us think*, Cambridge, Mass.: The Belknap Press.

Goldin-Meadow, S., Nusbaum, H., Kelly, S. D., & Wagner, S. (2001). Explaining math: Gesturing lightens the load. *Psychological Science, 12,* 516-522.

Hommel, B., Musseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action planning. *Behavioral & Brain Sciences, 24,* 849-937.

Jonides, J., Lewis, R. L., Nee, D. E., Lustig, C. A., Berman, M. G., and Moore, K. S. (2008). The mind and brain of short-term memory. *Annual Review of Psychology, 19,* 193-224.

Kang, S., Tversky, B. & Black, J. B. (2013) Gesture and speech in explanations to experts and novices. Submitted.

Kessell, A. M. & Tversky, B. (2006). Using gestures and diagrams to think and talk about insight problems. In R. Sun and N. Miyake (Eds) *Proceedings of the 28th Annual Conference of the Cognitive Science Society*. P. 2528.

Krauss R. M. & Hadar U. (2001). The role of speech-related arm/hand gestures in word retrieval. In R. Campbell & L. Messing, (Eds.) *Gesture, speech, and sign*. Pp. 93-116. Oxford: Oxford University Press.

Lee, P. U. and Tversky, B. (2005). Interplay between visual and spatial: the effect of landmark descriptions on comprehension of route/survey spatial descriptions. *Spatial cognition and computation, 5,* 163-185.

McNeill, D. (1992). *Hand and mind: What gestures reveal about thought*. Chicago: University of Chicago Press.

Paivio, A (1986). *Mental representations: a dual coding approach.* Oxford: Oxford University Press.

Schwartz, D. L., & Black, J. B. (1996). Shuttling between depictive models and abstract rules: Induction and fallback. *Cognitive Science, 20,* 457– 497.

Taylor, H. A., & Tversky, B. (1992). Spatial mental models derived from survey and route descriptions. *Journal of Memory and Language*, *31*, 261-282.

Tversky, B. (2011). Visualizing thought. *Topics in Cognitive Science.* 3, 499-535.

Tversky, B., Heiser, J., Lee, P. and Daniel, M.P. (2009). Explanations in gesture, diagram, and word. In K. R. Coventry, T. Tenbrink, & J. A. Bateman (Editors), *Spatial language and dialogue*. Pp. 119-131. Oxford: Oxford University Press.

Vandenberg, S. G. and Kuse, A. R. (1978). Mental rotations: A group test of three-dimensional spatial visualization. *Perceptual Motor Skills, 47*, 599-604.

Wexler, M., Kosslyn, S. M., & Berthoz, A. (1998). Motor processes in mental rotation. *Cognition, 68,* 77–94.

Wohlschläger, A., & Wohlschläger, A. (1998). Mental and manual rotatation. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 397–412.