RESEARCH REPORT

Individual differences in mental rotation: what does gesture tell us?

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Abstract Gestures are common when people convey spatial information, for example, when they give directions or describe motion in space. Here, we examine the gestures speakers produce when they explain how they solved mental rotation problems (Shepard and Meltzer in Science 171:701–703, 1971). We asked whether speakers gesture differently while describing their problems as a function of their spatial abilities. We found that low-spatial individuals (as assessed by a standard paper-and-pencil measure) gestured more to explain their solutions than high-spatial individuals. While this finding may seem surprising, finer-grained analyses showed that low-spatial participants used gestures more often than high-spatial participants to convey "static only" information but less often than high-spatial participants to convey dynamic information. Furthermore, the groups differed in the types of gestures used to convey static information: high-spatial individuals were more likely than low-spatial individuals to use gestures that captured the internal structure of the block forms. Our gesture findings thus suggest that encoding block structure may be as important as rotating the blocks in mental spatial transformation.

Keywords Mental rotation · Individual differences · Gesture

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Introduction

The gestures speakers spontaneously produce when they talk offer a window onto their unspoken thoughts (Goldin-Meadow 2003). Gestures, taken together with speech, can reveal people's mental representations of a task, offering a good method for examining their problem-solving strategies on a wide range of tasks, for example, mathematical equivalence (Perry et al. 1988), conservation of quantity (Church and Goldin-Meadow 1986; Ping and Goldin-Meadow 2010), the Tower of Hanoi (Garber and Goldin-Meadow 2002; Beilock and Goldin-Meadow 2010), block placement in a puzzle (Emmorey and Casey 2001), mental rotation (Chu and Kita 2008, 2011; Hostetter et al. 2011; Ehrlich et al. 2006), mechanical reasoning (Hegarty et al. 2005), and rotating gears (Alibali et al. 2011; Perry and Elder 1997; Schwartz and Black 1996, 1999).

Gesture occurs particularly often when speakers talk about space (Feyereisen and Havard 1999). For example, Lavergne and Kimura (1987) found that adults used twice as many gestures when asked to talk about space (e.g., describe a route between two points) than when asked to talk about other topics (e.g., describe a story in a favorite book, or a school day routine). As another example, speakers produce more gestures when their speech contains many spatial prepositions (Alibali et al. 2001) than when it does not. In addition, speech is slower and involves more dysfluencies when speakers' gestures are restricted and

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they are asked to convey spatial information than when their gestures are restricted and they are asked to convey non-spatial information (Rauscher et al. 1996).

Although many studies have explored gesture's role in spatial thinking (Alibali et al. 2011; Chu and Kita 2008, 2011; Hegarty et al. 2005; Hostetter et al. 2011), few have examined individual differences in the rate and types of gestures speakers use when describing spatial problems. One exception is Hostetter and Alibali (2007), who found that individuals with low verbal skills and high-spatial visualization skills gestured more than individuals with high verbal skills and low-spatial skills (see also Vanetti and Allen 1988). Good spatial ability and/or poor verbal ability may lead problem-solvers to approach problems spatially, which may, in turn, be reflected in the speakers' high gesture rate. However, gesturing could also encourage spatial problem solving and lead to improved spatial skills (Alibali 2005; Alibali et al. 2011).

Mental rotation is defined as the ability to imagine rotating 2-D or 3-D representations of objects (Shepard and Metzler 1971) and is a key spatial skill that has been widely investigated for group-level patterns (e.g., Cooper 1976; Frick et al. 2009; Just et al. 2001; Kosslyn et al. 1990) and for individual differences (e.g., Casey et al. 1995; Collins and Kimura 1997; Jansen-Osmann and Heil 2007; Peters et al. 2006; Shepard and Cooper 1982). A great deal of research has focused on the link between motor processes (e.g., hand movements on a joystick, knob, or stick that rotates an object) and mentally rotating the object (e.g., Schwartz and Holton 2000; Sekiyama 1982; Wexler et al. 1998; Wohlschlager and Wohlschlager 1998). For example, Wexler et al. (1998) asked adults to mentally rotate 2-D geometric figures while holding a joystick with their right hand. The participants were instructed to turn the joystick in a clockwise or counterclockwise direction as they solved each problem. Error rates were lower and reaction times faster when the direction of their hand movement and the direction in which they mentally rotated the figure were congruent (see also Wohlschlager and Wohlschlager 1998).

Gesture is an action and, as such, is a natural medium for reflecting mental representations involving action (Goldin-Meadow and Beilock 2010). For example, Hostetter et al. (2011) found that adults produce more co-speech gestures when they imagine a rotated arrow in motion than when they imagine the arrow in its static end state. Chu and Kita (2008) explored gestures produced without speech (i.e., co-thought gestures) in a mental rotation study and found that participants produced gestures representing a hand manipulating an object as it moved (e.g., the index finger and thumb held as if holding and moving the object) early in the experiment. However, over the course of the experiment, the type, frequency, and location of the gestures changed; participants began producing gestures that represented only the movement of the object (e.g., a flat hand rotating as the object would) and not the agent of the action. Chu and Kita argue that the change in gestures over time reflects a change in motor strategy, from one involving the agent's hand moving the object to one involving only the moving object (i.e., a deagentivized motor strategy). Analysis of the verbal descriptions produced during the mental rotation task supported this hypothesis—people who produced many agentivized gestures also produced sentences with active transitive verbs and agent-explicit descriptions; in contrast, people who produced deagentivized gestures or who did not gesture at all produced sentences with intransitive verbs that omitted references to the agent.

The aim of our study was to examine whether individuals who differ in their ability to perform a mental transformation task also differ in the gestures they produce when describing how they solved the mental rotation task. Our study thus differs from that of Chu and Kita (2008), which focused on how gesturing changes over the course of a mental transformation experiment independent of the gesturer's spatial abilities. Our goal was to explore the gestures people produce as a function of their spatial abilities.

A mental rotation task involves four main phases: visually encoding the objects, rotating one object, comparing the two objects, and responding (Cooper and Shepard 1973; Wright et al. 2008; see also Xu and Franconeri in press). A recent training study by Wright et al. (2008) on spatial transformation skills showed that adults were able to transfer skills learned on a mental rotation task and a mental paper-folding task to novel stimuli. Crucially, the training effects were evident only for the reaction time intercepts and not for the slopes, which reflect spatial transformation processes. Wright et al. (2008) suggest that training has its greatest impact on the initial phase of the mental transformation process—encoding object structure (which is reflected in the intercepts)—and not on later phases—rotating the objects, or comparing the objects. Given these findings, individuals might be expected to differ not only in rotating or comparing objects, but also in encoding object structure. We might then expect to find differences between low- and high-spatial individuals in the initial phase of the mental transformation task (i.e., in object encoding), differences that might be reflected in their gestures.

If, as the findings from the Wright et al. (2008) study suggest, the way objects are encoded is a key feature that differentiates low- and high-spatial ability individuals, high-spatial ability individuals should represent static aspects of objects (specifically, those involving the parts of the blocks relevant to the later comparison) better than low-

spatial ability individuals. If this difference is reflected in gesture, we might expect the high-spatial group to use more object property gestures reflecting the detailed structure of the blocks used in Shepard and Metzler (1971) task. In contrast, if high- and low-spatial ability groups differ in the second phase (rotating the object) and those differences are reflected in gesture, the high-spatial ability individuals might use more gestures reflecting the dynamic aspects of mental transformation involved in the block rotation than the low-spatial ability individuals.

Methods

Participants

Thirty-three monolingual English-speaking adults participated in this study for course credit. All participants had normal or corrected to normal vision. The participants ranged in age from 18 to 25. Five participants produced no gestures; their data were consequently excluded from analyses.[1]

Stimuli

Mental Rotations Test: A (MRT-A)

We used the Mental Rotations Test form-A (Peters et al. 1995), redrawn from the Vandenberg and Kuse Mental Rotation Test (Vandenberg and Kuse 1978) to assess the spatial ability of individuals. This paper-and-pencil test contains figures taken from the Shepard and Metzler (1971) task. Each test item contains 5 figures: one target object and four test objects. Two of the test objects represent figures that are rotated versions of the target object. Participants need to find and mark the two figures that match the target figure. Answers were considered correct only if both figures were correctly identified. There were a total of 24 test items.

Mental Rotation Block Test

The objects used in this study were based on the stimuli in Shepard and Metzler (1971). The objects were created by gluing together 2.5-cm wooden cubes (visual angle 1.6 arc°). Visual angle for the individual parts of the figures ranged from 3.2 to 6.4°, based on the number of blocks (2, 3 or 4) each part contained. Ten different objects, their corresponding isomorphic matches (mirror reflections), and their identical matches were constructed (see Fig. 1 for

samples of objects). For each trial, a pair of solid wooden objects was presented. Each participant received 10 same and 10 different pairs of objects. For both the same and different trials, one of the objects was rotated 0°, 45°, 90°, 135°, or 180° around the y-axis. That is, each rotation angle was presented twice in same and different pairs, yielding 20 trials in total.

The objects were presented on a 36 cm × 15 cm × 28 cm platform. The platform subtended 22.6° of visual angle in width and 9.5° of visual angle in height. A 49.5 cm × 51 cm × 36 cm screen was constructed to block the presentation platform from view between trials.

Procedure

Each participant was tested individually in a quiet room. After completing the consent forms and the MRT-A, participants were seated at a table where the objects were presented on a platform, which was approximately at the participant's eye level. The experimenter stood behind the platform across from the participant. Before each trial, a screen blocked the presentation from the participant's view. During this interval, the experimenter placed two objects on the platform according to a preset trial order. Objects were positioned using previously prepared cardboard templates, which were placed on the top of the platform and indicated the exact position of each object for that trial. The experimenter then removed the screen to reveal the pair of the objects. Each object pair was visible for 10 s. The participant's task was to determine whether the objects were the same or not. After 10 s, with the objects still visible, the experimenter asked the participant, "Can you explain to me how you solved this problem?" No feedback was given to the participants regarding the accuracy of their responses. The same procedure was repeated for 20 trials, which were presented in a randomized order.

Coding

Speech

Native English speakers transcribed all speech verbatim for participants' responses to each trial. Speech for each trial was then coded for the type of information (static vs. dynamic) participants used when describing their solution strategy. Static components involved *object* (e.g., blocks, arms) and *location* (e.g., right side) information; dynamic components involved information about the movement of the objects, either *rotation* (e.g., rotate, turn) or *direction* (e.g., from left to right). Table 1 shows samples of speech coding.

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[1] Two of these five individuals were in the low-spatial group based on their MRT-A scores.

Fig. 1 Sample stimuli from the Mental Rotation block test

Table 1 Sample coding of two individuals' speech and gesture (one individual from each spatial group)

Group	Speech	Speech coding	Gesture	Gesture coding	Gesture-speech match
Low-spatial Ability	I just moved [1 the one on the right] [2 a little bit] to [3 more downward] and they look the same	Static: the one on the right	1. Index finger pointed at the right block	1. Pointing-static	1. Match
		Dynamic: a little bit to more downward			
			2. Index finger moved toward left a little bit	2. Iconic-dynamic	2. Match
			3. Flat hand facing down moved in a downwards motion	3. Iconic-dynamic	3. Match
High-spatial Ability	Flipped [1 the left one] again, [2 rotated it] about 45 degrees, [3 put them together] in my head and found that they're the same	Static: the left one	1. Index finger pointed at the left block	1. Pointing-static	1. Match
		Dynamic: rotated it about 45 degrees			
			2. Loose hand facing right moved in semi-circle in clockwise	2. Iconic-dynamic	2. Match
			3. Index finger pointed at the blocks	3. Pointing-static	3. Mismatch

Each sentence was transcribed and coded for the type of information (static vs. dynamic) it conveyed. The location of each gesture was marked by a number in the speech transcript), and each gesture was classified according to *type* (pointing vs. iconic), *referent* (static vs. dynamic), and its relationship to speech (same or different information)

Gesture

Each participant's gestures were transcribed for each trial. A change in the shape of the hand or motion signaled the end of a gesture. Two types of gestures were coded: (1) *Pointing* gestures involved extending the index finger to indicate an object or location (e.g., using the index finger to point to the right block). (2) *Iconic* gestures indicated the shape of an object, its placement in space, and/or its motion (e.g., moving an index finger in a circular movement following a clockwise direction).

Gestures were then classified according to the components of the mental rotation task captured by the hands:

Static gestures referred to objects, either pointing to one of the blocks or illustrating a property of the block (e.g., making a curved hand shape as the palm faces up); *dynamic* gestures referred to the rotation (e.g., a circular movement) or direction (e.g., a movement along one directional axis, from left to right or back and forth) of the movement. Although static gestures could have been used to represent the endpoint of a rotation action, they were not used for this purpose in our sample. Static iconic gestures were further categorized according to whether they referred to the whole object or to a piece of the object. We coded a static gesture as referring to the whole object when all four fingers of the hand were used (e.g., four fingers curved to

represent the entire curved block), and as referring to a piece of the object when a subset of fingers were used (e.g., L shape, index finger, and thumb together referring to top part of the object). Table 1 presents two examples of participants' gestures.

Reliability

The first author coded all speech and gesture. To test the reliability of the coding system, a second coder randomly chose and coded participants' responses for 14 % of the trials. Agreement between coders was 96 % ($k = .93$, $n = 93$ trials) for coding speech and 88 % ($k = .82$, $n = 65$) for coding gesture.

Results

We divided participants into low-scoring and high-scoring spatial groups using a median split on the MRT-A scores. The average MRT-A score for the whole group was 37.64 ($n = 28$, $SD = 18.42$) with a median of 35.5 (*range:* 0–87.5). The mean MRT-A scores were 23.49 ($SD = 9.16$) and 51.79 ($SD = 13.75$) for low- and high-scoring groups, respectively.[2]

Do the two spatial groups differ in their spoken explanations?

First, we analyzed the type of information low- and high-spatial groups produced in their speech. We found that whenever participants mentioned dynamic information in a trial, they also tended to mention static information (fewer than 1 % of trials contained dynamic only information without any static information), although the converse was not the case. As a result, we calculated the mean proportion of *static only information* in speech and the mean proportion of *dynamic information* (with or without static information) in speech for each participant. There were no differences in how often the two groups conveyed static alone or dynamic with or without static information in speech, $F(1, 26) = .198$, $p > .05$. Figure 2 presents the mean proportion of trials produced by each spatial group, categorized by whether the speech conveyed static only information or dynamic information (with or without static information).

Second, we analyzed whether the rotation angle had an effect on the type of information conveyed in speech. Our

[2] Although some researchers using MRT-A identify individuals as high ability if they score >50 % and low ability if they score ≤50 % (e.g., Geiser et al. 2006), we used the median split to divide participants into low- and high-scoring groups because of the distribution of scores in this sample (range: 0–87.5).
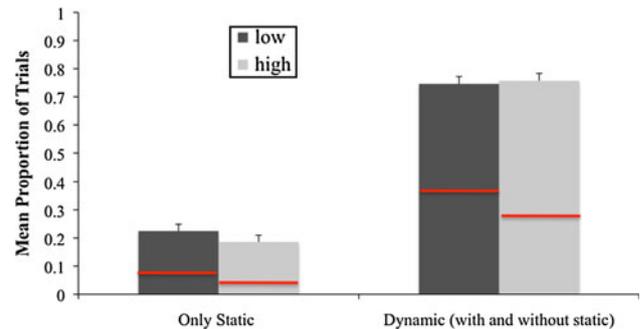
Fig. 2 The proportion of trials on which low-spatial (*dark gray bars*) and high-spatial (*light gray bar*) participants produced only static information or dynamic (with or without static) information in speech. The portion below the *red line* indicates the proportion of trials that was accompanied by a gesture (colour figure online)

preliminary analyses indicated that there were no differences in the type of speech used across angles that involved rotation (45°, 90°, 135°, and 180°), $F(3, 78) = 2.24$, $p > .05$. Thus, we collapsed the speech across these angle rotations. We then compared how often speech contained static only information versus dynamic information with or without static information for no rotation (0°) versus rotation (all angles) in the two groups. Results showed a main effect of angle, $F(1, 26) = 10.84$, $p < .01$, but no interaction between angle and spatial group, $p > .05$ (see Fig. 3). Individuals in both spatial groups produced more dynamic language when there was some rotation than when there was no rotation.

Do the two spatial groups differ in their co-speech gestures?

Overall, participants produced gestures on 239 of the 580 trials (41.2 %, $M = 8.53$, $SD = 6.23$, range: 1–20 trials). Thus, participants gestured on fewer than half the trials. We found that the low-spatial group produced gestures on more trials than the high-spatial group. The low-scorers gestured on 139 of their 280 trials (50 %), compared to 100 of the 280 trials for the high-scorers (36 %), $t(558) = 4.71$, $p = .001$.

In all but 24 of the 239 (90 %) trials containing gesture, the participants conveyed the same information in gesture as they conveyed in speech; 14 of these 24 trials were produced by the high-scorers and 10 by the low-scorers. When gesture did not convey the same information as speech (i.e., in these 24 trials), it added specificity to the static or dynamic information participants presented in speech. For example, one participant mentioned the direction of rotation (counterclockwise or clockwise) in gesture, while indicating only the movement in speech (i.e., "I turned the object"); another conveyed a specific part of the block with her hand shape (e.g., making a gesture of '3'

Fig. 3 The proportion of trials on which low-spatial (*left*) and high-spatial (*right*) participants produced only static information or dynamic (with or without static) information in speech as a function of angle rotation (i.e., no rotation vs. rotation)
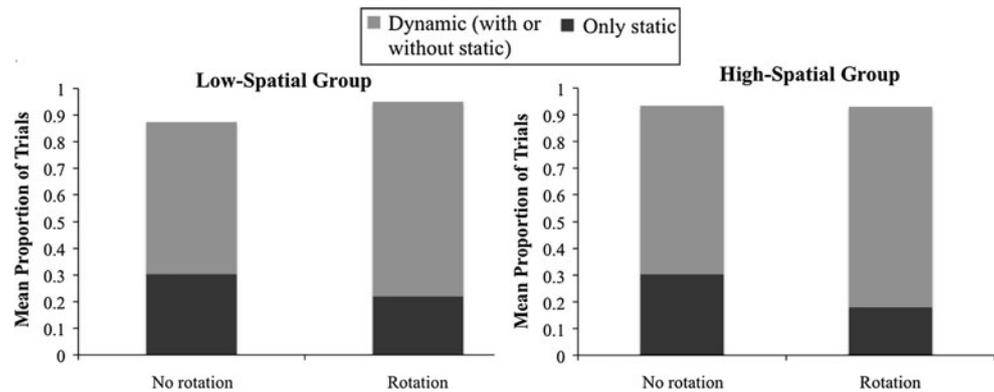
to present the top 3 pieces of the block), while indicating the whole object in speech (i.e., "The right block").

As in our speech analyses, we examined how often low- and high-spatial groups conveyed static only information and dynamic information (with or without static information) in gesture. Figure 4 displays the mean proportion of gesture trials produced by each spatial group, classified according to the information conveyed in gesture. The low-scoring spatial group produced a higher proportion of static only information in gesture (e.g., pointing to the blocks when talking about blocks), and consequently a lower proportion of dynamic information (e.g., producing a turning gesture when talking about turning a block), than the high-scoring spatial group, $F(1, 26) = 4.10$, $p < .05$, $\eta_p^2 = .14$. In addition, dynamic gestures were produced more frequently when there was an angle of rotation than when there was no rotation, $F(1, 18) = 7.91$ $p < .05$, $\eta_p^2 = .31$, and this effect did not differ for the two groups (see Fig. 5).

Having found a difference in how much static versus dynamic information the two spatial groups conveyed in gesture, we then analyzed the types of dynamic gestures (direction, rotation, or both) and static gestures (pointing, iconic, or both) individuals in each group produced. For
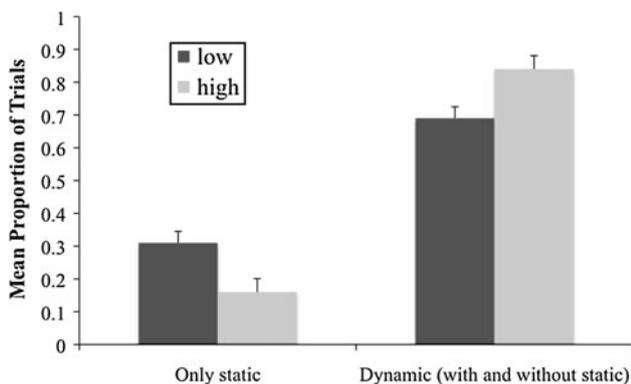

Fig. 4 The proportion of trials on which low-spatial (*dark gray bars*) and high-spatial (*light gray bar*) participants produced only static or dynamic (with or without static) information in gesture

each speech + gesture trial conveying dynamic information, we calculated whether low- and high-spatial individuals used direction (e.g., a left to right movement of the hand), rotation (e.g., a circular movement of the hand), or both in gesture. There were no reliable differences in the mean proportion of direction and rotation gestures the groups produced, $ts < .72$, $ps > .05$ (see Fig. 6). Not surprisingly, given that the participants produced few gestures that conveyed different information from the accompanying speech, we found that the participants' speech for the types of dynamic information paralleled the gesture patterns and that the groups did not differ in the mean proportion of rotation or dynamic information used in speech, $ts < 1.25$, $ps > .05$.

For each speech + gesture trial conveying static information, we calculated whether low- and high-spatial individuals used pointing gestures, iconic gestures, or both pointing and iconic gestures. There were no reliable differences in the mean proportion of iconic and pointing gestures the groups produced, $ts < .72$, $ps > .05$ (Fig. 7).

To examine whether groups differed in the types of object gestures they produced, we calculated the proportion of static iconic gestures that each participant used to represent whole objects versus pieces of the object and then (after subjecting the proportions to an arc-sine transformation) used a t test to compare the low- versus high-spatial groups. The high-scoring spatial group produced proportionally more gestures highlighting object parts (e.g., an L-handshape representing the arms of the blocks), and consequently fewer whole object gestures, than the low-scoring spatial ability group, $t(23) = 4.24$, $p < .01$. As shown in Fig. 8, the low-scoring spatial ability group generally gestured about the whole block (e.g., a curved handshape represented the left object); only 23 % (15 out of 67) of their iconic gestures specified a part or a spatial relation in an object. In contrast 83 % (35 out of 42) of the high-spatial group's static gestures referred to a part or relation in an object. Here again we found a parallel pattern in speech—the high-scoring spatial group used a greater

Fig. 5 The proportion of trials on which low-spatial (*left*) and high-spatial (*right*) scorers produced only static or dynamic (with or without static) information in gesture as a function of angle rotation (i.e., no rotation vs. rotation)
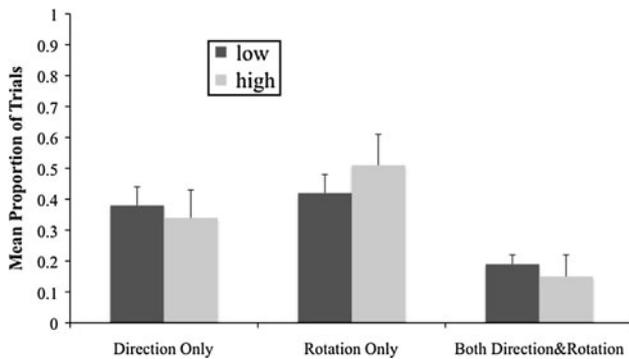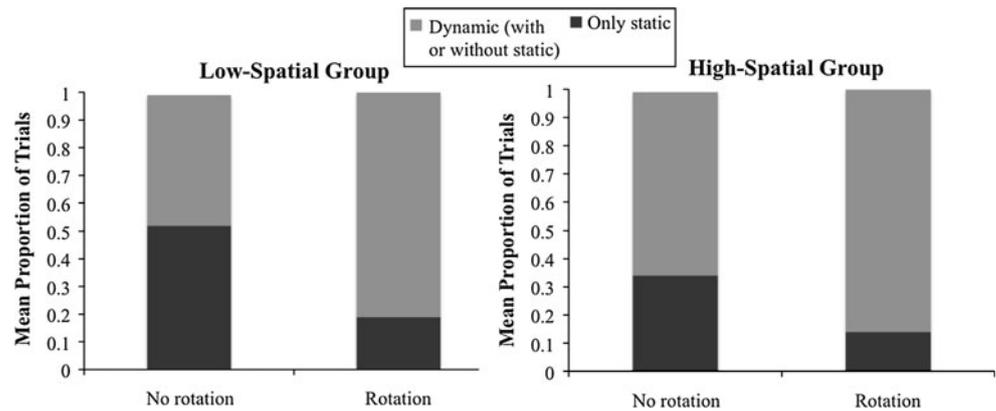
Fig. 6 The proportion of trials containing dynamic gestures, categorized according to the type of dynamic information (direction only, rotation only, both direction and rotation), conveyed by participants in the low (*dark gray bars*) and high (*light gray bar*) spatial ability groups
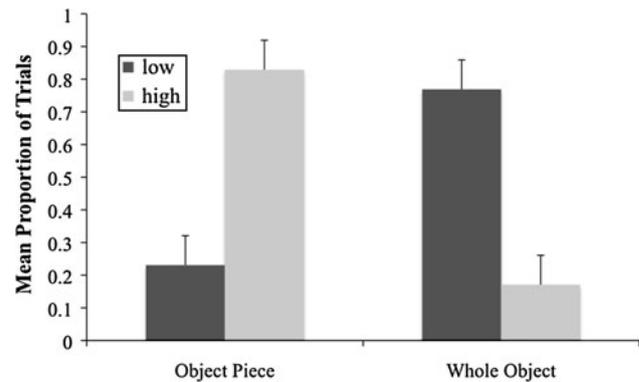
Fig. 8 The proportion of trials containing iconic gestures, categorized according to whether the gesture represent the whole object or a piece of the object, produced by participants in the low (*dark gray bars*)- and high (*light gray bar*)-spatial ability groups
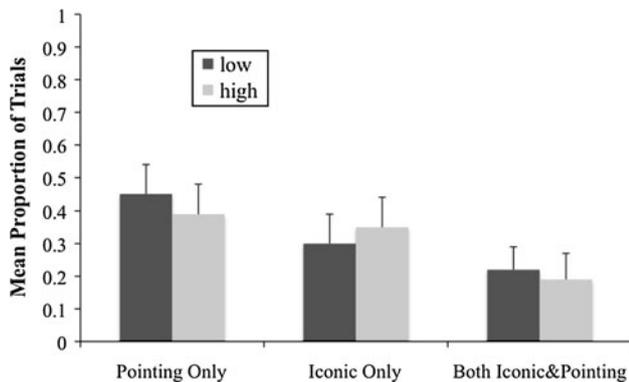
Fig. 7 The proportion of trials containing static gestures categorized according to the type of static information (pointing only, iconic only, both iconic and pointing) conveyed by participants in the low (*dark gray bars*)- and high (*light gray bar*)-spatial ability groups

proportion of words conveying static information to refer to specific object parts, and as a result a smaller proportion of words to refer to the whole object, than the low-scoring spatial group, $t(23) = 3.87$, $p < .01$.

Discussion

This study investigated differences in how individuals describe the solution strategies they used on a mental rotation task. More specifically, we asked whether the information conveyed in gesture varied as a function of the spatial abilities of the speaker.

Speakers of low- versus high-spatial ability differed in the number and types of gestures they produced on the task. On average, low-spatial ability individuals actually produced more gestures than high-spatial ability individuals. However, the low-spatial participants frequently used gestures simply to convey static information and gestured less often about dynamic information than the high-spatial participants. Furthermore, the low-spatial participants' static gestures were often iconic gestures that highlighted the entire structure of the block (e.g., a curved handshape gesture), whereas the high-spatial participants' iconic gestures emphasized the internal structure of the blocks (e.g., an L shaped gesture). These findings thus provide support for the two hypotheses with which we began our study: (1) Low- versus high-spatial individuals differed in

the types of static gestures they used to represent objects, thus reflecting a difference between groups in the first phase of the mental rotation task (visually encoding properties of the objects); (2) Low- versus high-spatial individuals differed in the proportion of dynamic gestures they used, thus reflecting a difference between groups in the second phase of the mental rotation task (dynamically moving the objects).

Wright et al. (2008) demonstrated that training on a mental rotation task had a more substantial impact on the initial process of mental transformation (encoding the object structure) than on later processes (i.e., rotating or comparing the objects). Our results align nicely with the idea that encoding the object structure is crucial to successful performance on a mental transformation task. Low- versus high-spatial individuals differed in the types of object property static gestures they used, but not in the types of dynamic gestures, even though, overall, high-spatial individuals produced more dynamic gestures. The specific-feature object gestures that the high-spatial group preferentially used may reflect their processing of important spatial information in preparation for transformation; encoding the block structure may be crucial to rotating the blocks in an informative way (Amorim et al. 2006; Hyun and Luck 2007). In other words, referring to the bottom three pieces of the whole block in gesture, and thus representing the detailed structure of the object, might make it easier to mentally rotate that object. The fact that the low-spatial individuals preferentially use whole-object gestures suggests that their representation of the object's structure may not contain the spatial detail necessary to successfully perform the transformation task. We speculate that the improvement in Wright's study may have been in low-spatial individuals who, as a result of training, began encoding the internal structure of the forms during the first phase of the task.

A recent developmental study by Ehrlich et al. (2006) on spatial transformations is consistent with our findings. 5-year-olds were tested on a mental transformation task that included items requiring rotation; the children were shown a two-dimensional divided shape and asked to choose (out of four possibilities) the whole shape that these two pieces would make if they were moved together. The children were also asked to describe how they solved the problem and most children gestured spontaneously during their descriptions. Children who performed better on this spatial task typically represented the movement of the pieces in dynamic gesture. Like the high-spatial adults in our study, who were more likely to gesture about dynamic information, encoding the movement in gesture (phase two of a mental transformation task) seemed to be associated with better performance in young children. In fact, requiring a different group of children to perform these dynamic gestures led to improvement on the same mental transformation task (although letting them observe an adult performing dynamic gestures did not, Goldin-Meadow et al. in press). This developmental pattern also aligns with findings in adults, who improved on a mental transformation task when instructed to gesture on the task (Chu and Kita 2011).

Our results do, however, appear to differ from Hostetter and Alibali (2007), who found that individuals with high-spatial visualization skills gestured more than individuals with low-spatial skills, although the different coding schemes used in the two studies make it difficult to directly compare the findings. Hostetter and Alibali focused exclusively on the numbers of representational gestures that their participants produced, whereas we analyzed the types of gestures, as well as the numbers, that our participants produced. In addition, Hostetter and Alibali (2007) assessed spatial skills in relation to verbal fluency and found that individuals with high spatial skills *and* low verbal skills gestured more than individuals with low spatial skills *and* high verbal skills. Since we assess only spatial abilities in our participants, it is difficult to directly compare our findings to Hostetter and Alibali's.

People's actions can influence how they think (e.g., Barsalou 1999; Beilock et al. 2008; Wilson 2002) and gesture, which is a type of action, is no exception. Gesturing has been found to have a causal effect on solving spatial problem by adding action information to mental representations (Beilock and Goldin-Meadow 2010; Goldin-Meadow and Beilock 2010) and has also been found to improve spatial reasoning by aiding spatial working memory (e.g., Chu and Kita 2011). For example, both children and adults remember more verbal and visuospatial items if they gesture while explaining their solutions to a math problem than if they do not gesture (Goldin-Meadow et al. 2001; Ping and Goldin-Meadow 2010; Wagner et al. 2004).

In order to make causal claims about gesture's function, it is necessary to manipulate gesture. As mentioned earlier, our study did not manipulate the gestures that the participants produced and, in fact, the participants produced their gestures after solving the problem. Thus, although the gestures the participants produced may have reflected their problem-solving skills, those gestures could not have played a role in the application of those skills (but see Goldin-Meadow et al. in press, who did manipulate gesturing in children and found that producing gesture improved children's performance on a mental rotation task). One interesting question for future research is whether encouraging low-spatial individuals to use their gestures to represent the internal structure of blocks (as our high-spatial group did) would change their performance on a mental rotation task.

Lastly, our study finds a tight coupling between the information conveyed in gesture and speech in a task involving mental transformation, as suggested by the Chu and Kita (2008) findings. Of the 239 trials on which the participants produced gestures, only 12 (5 %) were produced without speech (i.e., gesture always occurred with speech). Moreover, the gestures that the participants produced conveyed the same information as was conveyed in the accompanying speech in all but 24 of the 239 trials (10 %). The speech-gesture pattern in our study is thus different from many previous studies of spatial tasks, for example, Emmorey and Casey's (2001) study of adults telling another person where to place blocks, and Sauter et al. (2012) study of children and adults telling another person about the layout of a simple space. Both groups found that the speaker often conveyed spatial information in gesture that was *not* found in the accompanying speech. Future work is needed to understand when gesture does, or does not, go beyond speech.

In conclusion, we examined the gestures used in a mental rotation task by both low- and high-spatial ability adults. High-spatial individuals produced more dynamic gestures and fewer static gestures overall than low-spatial individuals, but their static gestures were more likely to convey the structure of objects. These findings suggest that encoding object structure may be as important as rotating the object to succeed on a mental spatial transformation task.

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