The Role of Spontaneous Gestures in Spatial Problem Solving

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Abstract. When solving spatial problems, people often spontaneously produce hand gestures. Recent research has shown that our knowledge is shaped by the interaction between our body and the environment. In this article, we review and discuss evidence on: 1) how spontaneous gesture can reveal the development of problem solving strategies when people solve spatial problems; 2) whether producing gestures can enhance spatial problem solving performance. We argue that when solving novel spatial problems, adults go through deagentivization and internalization processes, which are analogous to young children's cognitive development processes. Furthermore, gesture enhances spatial problem solving performance. The beneficial effect of gesturing can be extended to non-gesturing trials and can be generalized to a different spatial task that shares similar spatial transformation processes.

Keywords: gesture, spatial problem solving, mental rotation, cognitive development.

1 Introduction

We often spontaneously produce gestures when we speak. It has been proposed that people produce gestures in order to help their listeners better understand their verbal messages [1], [2]. Gestures are also found to benefit the speaker him or herself, such as facilitating conceptual planning [3], [4], [5]. That is, gestures help speakers to explore and organize spatio-motoric information during the thinking for speaking processes. Several studies have shown that individuals produce gestures more frequently when the complexity of conceptual planning of speaking increases [3], [4], [5]. Therefore, gesture can play an important role in the thinking process for speaking.

1.1 Gesture Reveals the Thinking Process

Gestures that spontaneously accompany speech can be a window into a speaker's mind, especially the speaker's analogue imagistic thinking [6]. Garber and Goldin-Meadow [7] showed that when adults were asked to explain their solution of the

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Tower of Hanoi problems, they sometimes produced gesture-speech mismatches, where gesture indicated one path and speech conveyed another path. These gesture-speech mismatches could be used to indicate whether the problem solver was considering alternative strategies. In another study, Alibali et al. [8] asked adults to explain how they solved some algebra word problems about discrete and continuous constant change. The authors found that when gesture and speech conveyed different mental representations of the problem, participants were more likely to use a strategy that was consistent with the representation in gestures. Thus, gestures can provide insight into the choice of problem solving strategies.

People also produce gestures while silently solving problems [9], [10]. These "co-thought" gestures (as opposed to "co-speech" gestures) are less studied. However, as we will review in Section 2, they can also reveal thought processes of problem solvers, for example, the strategies chosen [11].

1.2 Gesture Facilitates the Thinking Process

Co-speech gestures can facilitate learning. For example, telling children to gesture either before or during instruction makes them more likely to profit from that instruction [12], [13]. In Section 3, we will review evidence from our recent experiments [14] and other studies on how co-speech and co-thought gestures can enhance performance in spatial problem solving. We propose that people spontaneously produce gestures when they have difficulty in solving spatial problems. Gestures enhance performance of spatial tasks by improving the internal computation of spatial transformations.

2 Development of Problem Solving Strategy in Mental Rotation

People often spontaneously produce gestures when they solve problems regarding spatial transformations [15]. In Chu and Kita [11], two Shepard & Metzler type mental rotation tasks [16] were used to investigate how gesture can reveal the development of problem solving strategy over the course of the experiment. In a communicative mental rotation task (Fig. 1a shows an example), participants were asked to describe how the left three-dimensional object could be rotated to the position of the right one. This was described to the experimenter who sat next to the participants. They were required to describe the axis, direction, and angles of rotation. No feedback was given to the participants concerning the accuracy.

In the other non-communicative mental rotation task, participants were asked to participants were asked to match the stimulus object to one of the two mirrored three-dimensional objects, by pressing the correspondent left or right foot pedal. (Fig. 1b shows an example). The instructions did not mention gesture. The participants solved the problems alone in a room, and their spontaneous co-thought gestures were captured by a hidden camera. No feedback was given concerning the accuracy of the response.

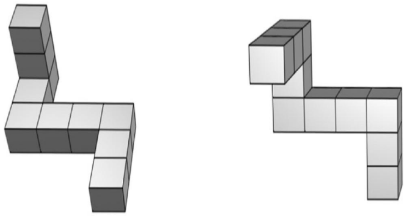

Fig. 1a. An example of a stimulus in the communicative mental rotation task

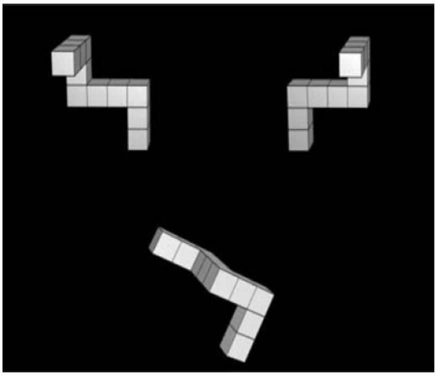

Fig. 1b. An example stimulus of the non-communicative mental rotation task

We hypothesized that adults go through three stages when they learn to solve novel spatial problems. In the first stage, adults produce gestures to simulate the manipulation of the stimulus object with their hands. Such a strategy provides adults with first–hand sensori-motor experiences about the consequence of the interaction between hand and object. In the second stage, people stop simulating grasping or manipulating the stimulus object, and start to use their hands to represent the stimulus object and move or rotate their hands to represent movements of the stimulus object. In this stage, gestures no longer represent an agent who manipulates an imaginary object; that is, gestures only represent the object's rotation. We call this change "deagentivization". In the third stage, the knowledge gained through the first two stages becomes internalized. People do not need to rely on gestures, and are able to solve the problems by pure internal models. We call this change "internalization".

To test our three stages hypothesis, we investigated two types of spontaneous gestures: (1) hand–object interaction gestures, which were those representing the manual exploration and manipulation of the stimulus object. This type of gestures had to have a grasping or holding hand shape (e.g., the index finger and the thumb were opposed or the two palms were opposed, as if to grasp or hold the object). These hand–object interaction gestures reflect the first stage problem solving strategy, in which participants simulated the manual exploration and manipulation of the stimulus object; (2) object–movement gestures, which were those depicting the axis, angle, and direction of rotation without any grasping or holding hand shape (e.g. a flat hand representing the object rotated around the wrist, or a hand with the extended index finger drew a circle in the air to represent rotation). These object–movement gestures reflected the second stage problem solving strategy, in which the agent disappeared from the gesture representation.

2.1 Evidence for the Deagentivization Process

To gain evidence for the deagentivization process, we investigated the appearance order of the two types of gestures in two time scales: within a single trial, and over the course of the entire experiment. According to our hypothesis, participants should produce hand–object interaction gestures earlier than object-movement gestures, as the agent disappears from the gesture representation.

First, if participants went through the deagentiviation within a single trial, they should produce hand–object interaction gestures earlier than object-movement gestures. We chose the trials that have at least one hand–object interaction gesture and one object-movement gesture. Then a score was given to each gesture according to its position in the trial. For example, if there were three gestures in one trial, the first gesture was given a score 1 and the last gesture was given a score 3. Thus, the higher the score, the later in the trial the gesture was produced. The mean position score of hand–object interaction gestures was significantly lower than that of object-movement gestures. Thus, within one single trial hand–object interaction gestures occurred significantly earlier than object-movement gestures.

Second, if participants deagentivized their external motor strategy over the course of the experiment, hand–object interaction gestures should occur in the earlier stage of the experiment than object-movement gestures. In this analysis, we focused on two types of trials, that is, the hand–object interaction gesture trials (i.e. trials with at least one hand–object interaction gesture but no object-movement gesture) and the object-movement gesture trials (i.e. trials with at least one object-movement gesture but no hand–object interaction gesture). We used trial numbers to indicate where in the experiment these two types of trials appeared. The larger the trial number, the later the trial occurred. The mean trial number of hand–object interaction gesture trials was significantly lower than that of object-movement gesture trials. Therefore, participants produced hand–object interaction gestures significantly earlier than object-movement gestures over the course of the experiment. Thus, both within a single trial or over the course of the experiment, the external motor strategy becomes deagentivized over time.

The above results were found in both the communicative and the non-communicative mental rotation tasks. The results support the first two stages of our three-stage hypothesis. Namely, when solving novel mental rotation problems, people initially simulate manipulating the stimulus object by hand. Later, people become able to use their hand to represent the stimulus object. At this stage, the agent of hand movements disappears and the gestural representation becomes more self-contained.

The deagentivization process is compatible with the idea that people go through a schematization process in problem solving, in which irrelevant information is removed from the gestural representation over practice [17]. In Schwartz and Black [17], participants were asked to describe their solution of interlocking gear problems. The authors found that people initially splayed their fingers on both hands and then rotated their hands to simulate the rotation of the gears. Then, over the course of the experiment, people started to produce simple “ticking” gestures, which marked off each gear without representing the rotational movements of the gears. At this stage, people solve the gear problem simply by counting whether the number of gears was odd or even. During this “schematization” process, people dropped the representation of the rotational movements, which was not directly relevant to the solution. Similarly, during the deagentivization process found in our current study, information about the agent, which was not logically necessary for the solution of the mental rotation task, was dropped from the gestural representation.

The deagentivization process can be also seen as an instance of increased "symbolic distance", as describe in Werner and Kaplan [18]. They proposed that at the early stage children are not able to separate the “symbols” (depicting element) from the “referents” (depicted content). For example, children at this developmental stage may seek to gain an object by trying to reach or grasp the object by himself or herself. Children then go through the "symbolic distancing" process, in which symbols become separated from the referents, available to be used freely without anchoring to the external referents. Now children can point at an object in order to get it. In our present study, object-movement gestures do not directly represent the way one might interact with the object. In this sense, they are one step removed from the referent as a symbol. Furthermore, we found that object movement gestures were produced physically further away from the computer screen than object movement gestures. Thus, object movement gestures are both symbolically and physically further away from the imaginary movement of the object on the computer screen.

2.2 Evidence for the Internalization Process

According to our three-stage hypothesis, people finally become able to solve the problem by using internal models over practice, and gestures are no longer needed. If so, participants’ external motor strategy, in the form of spontaneous gestures, should gradually become internalized over the course of the experiment task. We examined how gesture rates (number of gestures per minute) changed over the two trial halves of the experiment. The rates of both hand–object interaction gestures and object–movement gestures were lower in the second half than in the first half of the experiment. Thus, the rates of both types of gestures decreased over the course of the experiment. This result was found both in the communicative and the non-communicative mental rotation tasks [20]. This suggested that as participants became more experienced with the mental rotation task, the external motor strategy became internalized and no longer required overt hand movements.

Our results are in line with the view that an internal model that is decoupled from external motor strategies developed over the course of the mental rotation task. In Wexler et al. [19], the authors showed that manually rotating a joystick while solving a mental rotation task could enhance performance if the two rotations were in the same direction. However, the interaction between the directions of the manual and mental rotation disappeared in later trials. This leads the authors to suggest that an internal model that was not coupled to the external motor strategies developed over practice. Furthermore, our results are also compatible with Piaget [20] proposal of the “internalization” process in children’s cognitive development. According to Piaget, children gain knowledge of the physical world through repeatedly acting upon objects and the environment. When a certain action is repeated and generalized, it becomes an internalized scheme. Such internalized schemes are free from the constraints of the physical world and can be used efficiently to accomplish increasingly complex cognitive tasks.

Studies of human movement control have suggested that an internal model that accurately predicts the sensory consequences of motor commands is essential in performing complex human movements [21]. By using such an internal model, individuals can plan and control the grip forces required to stabilize objects [22], [23]. Furthermore, such an internal model has been found to play an important role in cognitive functions as well. Rieser et al. [24] found that locomotion even in the absence of vision facilitates the egocentric re-representation of spatial layout. Evidence from a neuroimaging study by de Lange, Hagoort and Toni [25] supported the existence of an internal model in mental rotation tasks, and such an internal model is independent of actual hand movements. The authors showed that the dorsal precentral gyrus is responsible for generating internal models for motor plans, whereas the primary motor cortex deals with the actual movement execution. Thus, the dorsal precentral gyrus may also be responsible for the internalized motor strategy in the mental rotation task in Chu and Kita [11].

3 Gesture Enhances Performance in Mental Rotation

Previous research has shown that forced hand movements can facilitate spatial problem solving when the movement is congruent with the required spatial transformation [26], [19]. In these studies, however, participants were forced to manually rotate an object in particular ways (e.g., turning a knob clockwise or anticlockwise) in every trial. In Chu and Kita [14], we investigated whether difficulty triggered spontaneous gestures and whether gestures improved performance in spatial problem solving. We also investigated whether the beneficial effect of gestures was specific to a particular type of spatial problem or it could be generalized to other spatial problems that shares similar spatial transformation processes.

3.1 Difficulty Triggers Gestures in Spatial Problem Solving

In Experiment 1 of Chu and Kita [14], participants were given the same mental rotation task as used in Chu and Kita [11]. The most robust findings in mental rotation studies have been that he difficulty of mental rotation increases monotonically with the angle of rotation [16], [27]. We replicated this finding In Experiment 1 of Chu and Kita [14]. Participants took longer time to solve the problems and made more errors in 120° and 240° rotation trials than in 60° and 300° rotation trials. Thus, 120° and 240° trials were harder than 60° and 300° trials. We performed this analysis based on nongesturing trials to establish the difficulty of the four angles independently of gesturing. We then analysed the rates of representational gestures (number of representational gestures per minute). In Chu and Kita [14], representational gestures were the hand movements that represented the interaction between the hand and objects, represented the perceptual and motion information of the objects themselves, or pointed at the objects. We found that participants produced spontaneous representational gestures more frequently in 120° and 240° rotation trials than in 60° and 300° rotation trials. Thus, the results were consistent with the idea that people spontaneously seek help from gesture when they have difficulty solving spatial problems. However, it is possible that gesture is merely an externalized reflection of the spatial thinking process. That is, the harder the spatial thinking is, the more gestures produced as by-products of the effortful spatial thinking process. In order to rule out this possibility, we conducted an experiment described in the next section.

3.2 Gesture Improves Performance in Spatial Problem

To provide direct evidence that gestures are functional in spatial thinking, in Experiment 2 of Chu and Kita [14], we manipulate the availability of gestures to examine the functional role of gesture on mental rotation performance. Participants were given two identical blocks of the same mental rotation task as used in Experiment 1, except that the length of each trial was fixed in order to eliminate a possible speed–accuracy trade-off.

In the first block, participants were assigned to the following three groups: (a) the gesture-encouraged group, in which participants were told that they could move their hands to help them when necessary; (b) the gesture-prohibited group, in which participants were required to put their hands under their legs to prevent gestures; (c) the gesture-allowed group, in which gesture was not mentioned in the instructions, although participants' hands were not restricted. The gesture-encouraged group solved more mental rotation problems correctly than the other two groups. Thus, gesture improves mental rotation performance.

In the second block, all three groups were asked to sit on their hands while solving the same mental rotation problems. We examined whether the beneficial effect of gesturing was confined to the trials in which the gestures were produced or if it extended to the subsequent non-gesturing trials. We found that the previous gesture-encouraged group solved more mental rotation problems correctly than the gesture-prohibited group and the gesture-allowed group. This result indicates that gesture facilitates the internal computation of spatial transformations in spatial problem solving. In addition, the result cannot be explained by the idea [28] that gesture facilitates spatial problem solving only by offloading the intermediate representation of the stimulus object to the gesturing hand.

Our results are compatible with the findings that gesture plays an active role in children's learning process [12], [13], [29]. For example, children who were encouraged to gesture when explaining their answers to a series of mathematical problems were more likely to improve after the subsequent instruction session, compared with those who were told not to gesture [13]. In another study, children who were required to produce gestures that contained a correct strategy for solving mathematical problems improved more on the post-test than children who were required to produce gestures that contained a partially correct strategy [12]. However, merely encouraging children to gesture was not sufficient to lead to improvement, as the gesture-encouraged group did not perform better than the control groups at the manipulation phase prior to the instruction phase. In contrast, the present study showed that when adults could benefit from gesturing without telling them how to solve mental rotation problems. Perhaps children did not have any prior knowledge on how to solve mathematical problems, and therefore they have to receive verbal instructions in order to benefit from gestures. However, adults in the present study knew how to solve mental rotation problems, and therefore encouraging them to gesture could immediately improve their mental rotation performance.

3.3 The Benefit of Gesturing Is Problem-General

In Experiment 3 of Chu and Kita [14], we investigated whether the benefit of gesturing can be generalized to new spatial tasks that share similar spatial computation processes with the mental rotation task. The procedure of Expereiment 3 of Chu and Kita [14] was the same as Experiment 2, except that we replaced the second mental rotation block in Experiment 2 with a paper folding task (Fig. 3 shows an example). The paper folding task [30] requires participants to mentally fold a square piece of paper, in the manner illustrated by the dotted lines in Figure 3. Participants then imagine a hole being punched through the folded paper in a location indicated by a circle, and then mentally unfold the piece of paper. Finally, they choose, from five options, the pattern that correctly shows what the paper would look like when it was unfolded. It has been proposed that the mental rotation task and paper folding task require similar spatial transformation processes, [31]. Individuals' performance on the two tasks significantly correlates [32].

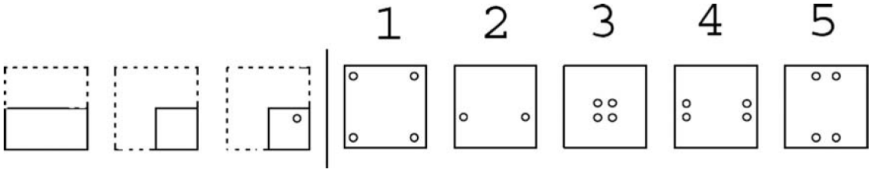

Fig. 3. An example stimulus of the paper folding task

The participants who were encouraged to gesture in the first mental rotation block solved more paper folding problems correctly than those who were not encouraged to gesture. Thus, the benefit of gesturing can be generalized to a different spatial task that requires similar spatial transformations.

The above results are in line with the finding that spatial training generalizes to transformations of new objects and new tasks that involve some of the same spatial transformations [33], [34]. For example, [35] found that participants who practiced on a mental rotation task performed significantly better on medical surgical tasks that rely on multiple mental and manual rotations than participants who did not receive mental rotation training. However, transfer effects usually occurred after several hours of practice. In contrast, in Chu and Kita [14], when participants were encouraged to gesture in the mental rotation task for about 10 minutes, they were able to transfer the gestural benefit to the subsequent paper folding task.

4 How Gesture Improves Spatial Problem Solving

The exact mechanism underlying the beneficial effect of gesture on spatial problem solving is unclear from the above mentioned studies. However, the results allow us to speculate about the possible ways that gesture could facilitate spatial problem solving. To solve spatial tasks like mental rotation or paper folding tasks, one need to execute multiple steps of mental spatial transformations, and hold these intermediate representations in the working memory [36], [37], [38], [39]. Thus, gesture may facilitate spatial problem solving either by facilitating spatial working memory or by improving the internal computation of spatial transformations. Of course, gesture can benefit both as well.

Previous research has shown that gesture can reduce working memory load during speaking [28], [40]. Therefore, when solving spatial problems, people may off-load the intermediate representations of spatial transformations to the gesturing hand so that the chance of forgetting these representations is reduced. However, the off-loading theory alone cannot account the fact that the beneficial effect of gesture did not disappear in the subsequent nongesturing mental rotation and paper folding tasks. Producing gestures must have improved more general spatial transformation skills.

Gesture, as a simulated action [41], can help people link their existing sensori-motor experience with the spatial transformation process that is required to solve the problems. Previous studies have demonstrated that adults' knowledge about a physical event can be constructed through imagined actions on the physical object [42], [43]. People were better at judging the physical property of water in a glass when imaging holding the glass in their hand [44]. In Chu and Kita [14], participants' hand-object interaction gestures may help people to use their rich experience of grasping or manipulating objects to compute more accurate information regarding how the object could be rotated by hand for different axes, angles, and directions.

Furthermore, gesture can highlight perceptual information that is encoded in the gesture In Chu and Kita [14], object-movement gestures would allow people to tap into their knowledge or how their hands look from different angles. This knowledge can be used to predict the appearance of an object under rotation and become better at judging the relative location of parts and the orientation of planes during rotation. This leads to a more accurate prediction of how the object would look when it was rotated on a given axis for certain degrees and directions.

The deagentivization process might contribute to the generalization of the gestural benefit from one spatial task to another. Hand-object-interaction gestures, which simulate the real action on the stimulus object, might serve as a good initial tool to link our sensori-motor experience of manual action on an object to the problem being solved. However, this strategy is restricted by physical features of the object, such as the size, location, and orientation. In contrast, producing object-movement gestures might be a more efficient strategy than producing hand-object-interaction gestures because the representation of the agent and other details that are only relevant to a particular stimulus object are dropped from the object-movement gestures. By using the hands to represent the movement of an object without including information about how the object would be held, object-movement gestures increases the chance of generalizing the spatial transformation processes beyond one particular spatial problem.

The internalization process might contribute to the lasting beneficial on the second mental rotation block in Experiment 2 of Chu and Kita [11]. As the external motor strategy of the gesture-encouraged group became internalized towards the end of the first mental rotation block, participants were able to solve spatial problems with more efficient with internal models. Thus, the benefit gained from gesturing in the first mental rotation block can be extended to the subsequent non-gesturing blocks. Here, we speculate two possible internal models that the gesture-encouraged group might use when they were prohibited from gesturing. Firstly, when gesture was not allowed, the gesture-encouraged group might use imagined hand movements to simulate the manipulation of the stimulus object or simulate the rotation of stimulus object. Secondly, in the non-gesturing mental rotation and paper folding blocks, people might drop the representation of their hands totally, and solve the problems by mentally imagining the rotation of the stimulus object along certain axes. Future studies are needed to further test these two possible internal models.

5 Conclusions

In this article, we discussed the findings from two of our recent studies [11], [14], in which we examined the role of spontaneous gestures in spatial problem solving. We first reviewed evidence on how gestures reveal the development of problem solving strategies in a mental rotation task. The results indicate that adults go through deagentivization and internalization processes when solving novel spatial problems. At the begining, people use their gestures to simulate the manual manipulation of the stimulus object. Then the gestural representation becomes deagentivized. That is, the agent is dropped from the gestural representation, and people use their hands to represent the stimulus object and rotate their hands to represent the object rotation. Finally, the problem solving strategy becomes internalized. Overt gestures are no longer needed, and people can solve the problems by internal models.

Furthermore, we reviewed evidence on how gesture enhances performance in spatial problem solving. We found that people spontaneously produce gestures to help them solve difficult spatial problems, and encouraging people to gesture can enhance their performance. The benefit gained from gesturing can extend to subsequent problems in which gesturing is prohibited, and the beneficial effect can also generalize to a different spatial task that requires similar spatial transformations.

In sum, our findings indicate that people spontaneously use gestures to facilitate spatial problem solving. Over practice, the spatial computation supported by overt gestures becomes deagentivized and eventually internalized. Such processes improve the internal computation of spatial transformation in a problem-general way.

References

1. Kendon, A.: Do gestures communicate? A review. Research on Language and Social Intraction 27, 175–200 (1994)
2. Kendon, A.: Gesture: Visible Action as Utterance. Cambridge University Press, Cambridge (2004)
3. Hostetter, A.B., Alibali, M.W., Kita, S.: I see it in my hands' eye: Representational gestures reflect conceptual demands. Language and Cognitive Processes 22, 313–336 (2007)
4. Kita, S., Davies, T.S.: Competing conceptual representations trigger co-speech representational gestures. Language and Cognitive Processes 24, 760–775 (2009)

5. Melinger, A., Kita, S.: Conceptualisation load triggers gesture production. Language and Cognitive Processes 22, 473–500 (2007)
6. McNeill, D.: Hand and mind. University of Chicago Press, Chicago (1992)
7. Garber, P., Goldin-Meadow, S.: Gesture offers insight into problem-solving in adults and children. Cognitive Science 26, 817–831 (2002)
8. Alibali, M.W., Bassok, M., Solomon, K.O., Syc, S.E., Goldin-Meadow, S.: Illuminating mental representations through speech and gesture. Psychological Science 10, 327–333 (1999)
9. Saltz, E., Donnenwerth-Nolan, S.: Does motoric imagery facilitate memory for sentences? A selective interference test. Journal of Verbal Learning and Verbal Behavior 20, 322–332 (1981)
10. Hegarty, M., Mayer, S., Kriz, S., Keehner, M.: The role of gestures in mental animation. Spatial Cognition and Computation 5, 333–355 (2005)
11. Chu, M., Kita, S.: Spontaneous gestures during mental rotation tasks: Insights into the microdevelopment of the motor strategy. Journal of Experimental Psychology: General 137, 706–723 (2008)
12. Goldin-Meadow, S., Cook, S.W., Mitchell, Z.A.: Gesturing gives children new ideas about math. Psychological Science 20, 267–272 (2009)
13. Broaders, S.C., Cook, S.W., Mitchell, Z.A., Goldin-Meadow, S.: Making children gesture brings out implicit knowledge and leads to learning. Journal of Experimental Psychology: General 136, 539–540 (2007)
14. Chu, M., Kita, S.: The nature of the beneficial role of spontaneous gesture in spatial problem solving. Journal of Experimental Psychology: General 140, 102–116 (2011)
15. Trafton, J.G., Trickett, S.B., Stitzlein, C.A., Saner, L., Schunn, C.D., Kirschenbaum, S.S.: The relationship between spatial transformations and iconic gestures. Spatial Cognition and Computation 6, 1–29 (2006)
16. Shepard, R.N., Metzler, J.: Mental rotation of three-dimensional objects. Science 171, 701–703 (1971)
17. Schwartz, D.L., Black, J.B.: Shuttling between depictive models and abstract rules: Induction and fallback. Cognitive Science 20, 456–497 (1996)
18. Werner, H., Kaplan, B.: Symbolic formation. An organismic-developmental approach to language and the expression of thought. John Wiley & Sons, Inc., New York (1963)
19. Wexler, M., Kosslyn, S.M., Berthoz, A.: Motor processes in mental rotation. Cognition 68, 77–94 (1998)
20. Piaget, J.: Six psychological studies. Random House, NY (1968)
21. Wolpert, D.M., Ghahramani, Z., Jordan, M.I.: An internal model for sensorimotor integration. Science 269, 1880–1882 (1995)
22. Johansson, R.S., Riso, R., Hager, C., Backstrom, L.: Somatosensory control of precision grip during unpredictable pulling loads. Experimental Brain Research 89, 181–191 (1992)
23. Flanagan, J.R., Wing, A.M.: The role of internal models in motor learning and control: evidence from grip force adjustments during movements of hand-held loads. Journal of Neuroscience 17, 1519–1528 (1997)
24. Rieser, J.J., Guth, D.A., Hill, E.W.: Sensitivity to perspective structure while walking without vision. Perception 15, 173–188 (1986)
25. de Lange, F.P., Hagoort, P., Toni, I.: Neural topography and content of movement representations. Journal of Cognitive Neuroscience 17, 97–112 (2005)
26. Wohlschläger, A., Wohlschläger, A.: Mental and manual rotation. Journal of Experimental Psychology: Human Perception and Performance 24, 397–412 (1998)

27. Shepard, R., Cooper, L.: Mental Images and Their Transformations. MIT Press, Cambridge (1982)
28. Wagner, S.M., Nusbaum, H.C., Goldin-Meadow, S.: Probing the mental representation of gesture: Is handwaving spatial? Journal of Memory and Language 50, 395–407 (2004)
29. Cook, S.W., Mitchell, Z., Goldin-Meadow, S.: Gesturing makes learning last. Cognition 106, 1047–1057 (2008)
30. Ekstrom, R.B., French, J.W., Harman, H.H., Dermen, D.: Kit of Factor-Referenced Cognitive Tests. Educational Testing Service, Princeton (1976)
31. Hostetter, A.B., Alibali, M.W.: Raise your hand if you're spatial: Relations between verbal and spatial skill and gesture production. Gesture 7, 73–95 (2007)
32. Miyake, A., Friedman, N.P., Rettinger, D.A., Shah, P., Hegarty, M.: How are visuospatial working memory, executive functioning, and spatial abilities related? A latent variable analysis. Journal of Experimental Psychology: General 130, 621–640 (2001)
33. Leone, G., Taine, M.C., Droulez, J.: The influence of long-term practice on mental rotation of 3-D objects. Cognitive Brain Research 1, 241–254 (1993)
34. Wallace, B., Hofelich, B.G.: Process generalization and the prediction of performance on mental imagery tasks. Memory & Cognition 20, 695–704 (1992)
35. Stransky, D., Wilcox, L.M., Dubrowski, A.: Mental rotation: cross-task training and generalization. Journal of Experimental Psychology: Applied 16, 349–360 (2010)
36. Carpenter, P.A., Just, M.A.: Spatial ability: An information processing approach to psychometrics. In: Sternberg, R.J. (ed.) Advances in the Psychology of Human Intelligence, vol. 3, pp. 221–253. Erlbaum, Hillsdale (1986)
37. Hegarty, M., Sims, V.K.: Individual differences in mental animation during mechanical reasoning. Memory & Cognition 22, 411–430 (1994)
38. Salthouse, T.A., Babcock, R.L., Mitchell, D.R., Skovronek, E., Palmon, R.: Age and experience effects in spatial visualization. Developmental Psychology 26, 128–136 (1990)
39. Shah, P., Miyake, A.: The separability of working memory resources for spatial thinking and language processing: An individual differences approach. Journal of Experimental Psychology: General 125, 4–27 (1996)
40. Goldin-Meadow, S., Nusbaum, H., Kelly, S., Wagner, S.: Explaining math: Gesturing lightens the load. Psychological Science 12, 516–522 (2001)
41. Hostetter, A.B., Alibali, M.W.: Visible embodiment: Gestures as simulated action. Psychonomic Bulletin & Review 15, 495–514 (2008)
42. Gibbs Jr., R.W.: Embodiment and cognitive science. Cambridge University Press, Cambridge (2006)
43. Shapiro, L.: The embodied cognition research programme. Philosophy Compass 2, 338–346 (2007)
44. Schwartz, D.L., Black, T.: Inferences through imagined actions: Knowing by simulated doing. Journal of Experimental Psychology: Learning, Memory, and Cognition 25, 116–136 (1999)