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How Do Gestures Influence Thinking and Speaking? The Gesture-for-Conceptualization Hypothesis

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People spontaneously produce gestures during speaking and thinking. The authors focus here on gestures that depict or indicate information related to the contents of concurrent speech or thought (i.e., representational gestures). Previous research indicates that such gestures have not only communicative functions, but also self-oriented cognitive functions. In this article, the authors propose a new theoretical framework, the gesture-for-conceptualization hypothesis, which explains the self-oriented functions of representational gestures. According to this framework, representational gestures affect cognitive processes in 4 main ways: gestures activate, manipulate, package, and explore spatio-motoric information for speaking and thinking. These four functions are shaped by gesture's ability to schematize information, that is, to focus on a small subset of available information that is potentially relevant to the task at hand. The framework is based on the assumption that gestures are generated from the same system that generates practical actions, such as object manipulation; however, gestures are distinct from practical actions in that they represent information. The framework provides a novel, parsimonious, and comprehensive account of the self-oriented functions of gestures. The authors discuss how the framework accounts for gestures that depict abstract or metaphoric content, and they consider implications for the relations between self-oriented and communicative functions of gestures.

Keywords: gesture, embodied cognition, speech production, spatial representation, problem solving

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People spontaneously produce gestures during speaking and thinking. Gestures play an important role in communication (Hostetter, 2011; Kendon, 1994), as speech and gesture jointly express the speaker's message in a coordinated way (Kendon, 2004; Streeck, 2009). Thus, gesture production is partly motivated by speakers' desire to enhance communication. However, a growing body of evidence shows that gesture production also affects gesturers' own cognitive processes and representations; that is, gestures also have self-oriented functions. The goal of this article is to outline a theoretical account of the self-oriented functions of gestures.

Theories of embodied cognition argue that human cognitive processes are rooted in the actions of human bodies in the physical world (Shapiro, 2014; Wilson, 2002). According to this perspective, cognitive processes are rooted in perception and action. We argue here that gestures are closely linked to practical actions, as they are generated from the same system. Moreover, gestures are physical actions of a special type, that is, representational actions. As such, gesture is involved in cognitive processes in important ways, which we describe herein.

There is wide agreement in the literature that gestures can be categorized into several subtypes (Efron, 1941; Ekman & Friesen, 1969; McNeill, 1992, 2005). Most research on the self-oriented functions of gestures focuses on representational gestures (though see Krahmer & Swerts, 2007, on beat gestures). *Representational gestures* are generally defined as gestures that depict action, motion, or shape, or that indicate location or trajectory. For example, as a speaker says, "she throws a ball," she might enact a throwing motion with her hand, or as she says, "the ball hit the wall and bounced back," she might trace the trajectory of the ball with her finger. Representational gestures may also metaphorically represent abstract concepts. For example, while saying "an opinion," a speaker might make a cup-like shape with his palm facing upward as if to hold an object, thus metaphorically representing an opinion as a graspable object. Representational gestures include iconic gestures, metaphoric gestures, and deictic gestures in the taxonomy described by McNeill (1992), and they are roughly equivalent to pantomimes, physiographic, ideographic, and deictic gestures in the system described by Efron (1941). Throughout this article, we

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use the term *gesture* to refer specifically to representational gestures.

Gesture for Conceptualization

What function do gestures serve for the person who produces them? Existing hypotheses regarding the self-oriented functions of gestures focus on how gestures facilitate speaking. Several distinct hypotheses have been proposed. First, the lexical retrieval hypothesis holds that speakers' gestures serve to increase activation on items in their mental lexicons, therefore facilitating lexical access (Hadar & Butterworth, 1997; Krauss, Chen, & Gottesman, 2000; Rauscher, Krauss, & Chen, 1996). According to this view, a gesture may activate spatial features that are a part of the semantic representation of a lexical item, and in so doing, prime retrieval of that lexical item. Second, the image activation hypothesis (de Ruiter, 1998; Freedman, 1977; Hadar & Butterworth, 1997) holds that gesture maintains visuospatial imagery. Because gesture prevents imagery from decaying, the speech production process has better quality information to inspect. Third, the information packaging hypothesis holds that gesture helps speakers package spatio-motoric information into units appropriate for verbal encoding (Kita, 2000). When communicating complex information, one needs to break the information down into chunks of a size manageable for the speech production process. One important planning unit for speech production is the clause (Bock & Cutting, 1992); thus, gestures help chunk information into units that can be encoded in a clause. Fourth, the cognitive load reduction hypothesis (Goldin-Meadow, Nusbaum, Kelly, & Wagner, 2001; Wagner, Nusbaum, & Goldin-Meadow, 2004) holds that gesture reduces the amount of cognitive resources needed for formulating speech. The scope of all of these theories is limited to speech production; however, a growing body of literature suggests that gesture's function in cognition goes beyond speaking.

There is abundant evidence that gesture is involved, not only in speaking, but also in learning and problem solving. When people explain their solutions to problems or think aloud as they solve, they often use gestures to highlight spatio-motoric representations (e.g., Beilock & Goldin-Meadow, 2010) or to express spatial strategies (e.g., Alibali, Spencer, Knox, & Kita, 2011). Gestures can introduce new strategies into people's repertoires of strategies (Goldin-Meadow, Cook, & Mitchell, 2009), bring out implicit knowledge in problem solving (Broaders, Cook, Mitchell, & Goldin-Meadow, 2007), and lead to lasting learning (Cook, Mitchell, & Goldin-Meadow, 2008). Some researchers have argued that gesture facilitates learning by reducing learners' cognitive load (Goldin-Meadow & Wagner, 2005).

People spontaneously gesture not only when they talk about their problem-solving processes (co-speech gestures), but also when they solve problems silently (co-thought gestures; Schwartz & Black, 1996; Hegarty, Mayer, Kriz, & Keehner, 2005).[1] Similar to co-speech gestures, these self-oriented co-thought gestures can reflect problem solving strategies (Alibali, Spencer, et al., 2011) and enhance problem solving performance (Chu & Kita, 2011). Moreover, there is evidence that co-speech and co-thought gestures are produced from the same underlying mechanism (Chu & Kita, 2016). Here, we propose that both co-speech and co-thought gestures have the same self-oriented functions.

We present a new theoretical framework, the gesture-for-conceptualization hypothesis, which proposes a role for gesture in both speaking and thinking. This new account places gesture in a more central position in human cognition, in contrast to accounts that focus only on the role of gesture in either language production or problem solving. We propose that gesture shapes the way people conceptualize information through four functions. The key theses of the gesture-for-conceptualization hypothesis are (a) gesture activates, manipulates, packages, and explores spatio-motoric information for the purposes of speaking and thinking and (b) gesture schematizes information, and this schematization process shapes these four functions.

According to the gesture-for-conceptualization hypothesis, gesture influences conceptualization in the sense that it affects the contents of thought in four ways. First, people use gesture to activate spatio-motoric information (e.g., Alibali & Kita, 2010). When there is a choice between using spatio-motoric representations versus other more abstract representations for speaking or thinking, producing gestures encourages people to rely more on spatio-motoric representations. Second, people use gesture to manipulate spatio-motoric information (e.g., Chu & Kita, 2011). Just as people use action to manipulate objects, people can use gesture to manipulate spatio-motoric information. Third, people use gesture to package spatio-motoric information into units useful for other cognitive operations. For example, when verbally expressing complex ideas, information needs to be linearized into small chunks, each of which can be verbally encoded in a clause. Gesture facilitates this process (e.g., Mol & Kita, 2012). Fourth, people use gesture to explore various possibilities for what information to focus on in activities that involve rich or complex spatio-motoric information. Finally, we maintain that the four functions depend on gestures being schematic representations, which focus on a small subset of information that is potentially relevant to the task at hand (Chu & Kita, 2008; de Ruiter, 2000; Goldin-Meadow, 2015; Novack, Congdon, Hemani-Lopez, & Goldin-Meadow, 2014).

The gesture-for-conceptualization hypothesis is based on our view of how gestures are generated—that is, the mechanism that gives rise to gestures. Unlike some theories that embed gesture generation within speech production processes (e.g., de Ruiter, 2000; McNeill, 2005), we propose that gestures are generated from the processes that also generate practical actions (e.g., grasping a cup to drink; Hostetter & Alibali, 2008; Kita, 2000, 2014; Kita & Özyürek, 2003) and, therefore, gestures share some properties with practical actions (Chu & Kita, 2016). Because thinking in terms of action has different properties from propositional or verbal thinking, gesture offers possibilities and perspectives that propositional or verbal thinking cannot, and therefore, gesture affects thinking in particular ways.

In the following sections, we describe the evidence for each of the four functions. We then consider how these functions are shaped by gesture schematizing information.

In considering evidence for the role of gesture in cognition, it is valuable to distinguish issues of mechanism and function, drawing

[1] "Co-thought" gestures do not include "silent gestures" (Goldin-Meadow & Brentari, 2016), which are produced for communicative purposes when speech is not available.

on the Aristotelian distinction between efficient cause and final cause. Efficient cause or mechanism is the process or operation that gives rise to a behavior, and final cause or function is the purpose that a behavior serves, or the consequence that a behavior brings about (see Hladký & Havlíček, 2013, for discussion). The most direct evidence for self-oriented functions of gestures comes from studies that demonstrate cognitive consequences of gesture by experimentally manipulating gesture production (e.g., by encouraging or prohibiting gesture). Less direct evidence comes from studies of the mechanisms that give rise to gestures. For example, some studies experimentally manipulate the difficulty of cognitive processes, and demonstrate that specific types of difficulty give rise to more gestures. Such findings suggest that gestures may be produced to facilitate the cognitive processes under study. Though indirect, this type of evidence is important because it can disconfirm hypotheses about self-oriented functions of gesture and inform us about what processes may benefit from gesture, complementing findings from studies that experimentally manipulate gesture production. In the following sections on the four functions of gestures, we first briefly present indirect evidence from studies on mechanism, and then present more direct evidence from studies that manipulated gesture production.

Gesture Activates Spatio-Motoric Information

According to the gesture-for-conceptualization hypothesis, producing gestures increases the activation level of spatio-motoric information during speaking and thinking. This can occur in two ways. First, gestures can help maintain the activation of spatio-motoric representations that are already active, so that these representations do not decay during speaking or thinking (de Ruiter, 1998; Hadar & Butterworth, 1997; Wesp, Hesse, Keutmann, & Wheaton, 2001). Second, gestures can activate new spatio-motoric representations—ones that were not previously active—and this can, in turn, change the content of speech or thought (see also Hostetter & Boncoddo, in press). Two lines of evidence, which we review below, support these claims. First, people produce more gestures when maintaining pre-existing spatio-motoric representations is challenging. Such findings provide suggestive but not definitive evidence that gesture activates spatio-motoric information. Second, as shown in studies that experimentally manipulate gesture production, producing gestures promotes the expression and use of new spatio-motoric information in speaking and problem solving. Such findings provide more direct, definitive evidence for this function of gesture.

Difficulty in Maintaining Spatio-Motoric Information Triggers Gesture

Several studies have shown that people produce more gestures when it is more difficult to maintain pre-existing spatio-motoric representation. For example, adults produce more gestures when describing line drawings or paintings from memory than when describing them with the stimuli visible (de Ruiter, 1998; Morsella & Krauss, 2004; Wesp et al., 2001). Along similar lines, children gesture more when they need to maintain spatial information in memory, such as when asked to remember the location of a toy (Delgado, Gomez, & Sarria, 2011).

Gesture Production Promotes Activation of Spatio-Motoric Information

Experiments in which gesture production is manipulated—for example, by prohibiting gesture—provide strong evidence that gesture activates spatio-motoric information. Two types of effects have been reported: gesture maintains pre-existing spatio-motoric representations (i.e., helps them resist decay) and gesture activates new spatio-motoric representations that were not previously active. We review evidence for each of these effects, in turn.

Producing gestures maintains activation of pre-existing spatio-motoric information. So and colleagues (2014) asked participants to remember a route on a diagram representing streets. During the retention period, participants rehearsed the route by silently gesturing or by visualizing it while holding a softball in each hand (prohibiting hand movements). Participants recalled the route better when they gestured than when they visualized without moving their hands. Thus, gesture helped maintain their pre-existing representation of the route.

Producing gestures also activates new spatio-motoric information. When people have a choice between using spatio-motoric versus non-spatio-motoric information, gesture production promotes the use of spatio-motoric information. That is, when people are free to choose the content of their speech, gestures activate spatio-motoric information that were not previously active, leading people to express more spatio-motoric content in speech. For example, in conversational interactions, the imagistic content of speech is greater when people are allowed to gesture than when they are not (Rime, Shiaratura, Hupet, & Ghysselinckx, 1984); people choose to talk about spatio-motoric content when they are free to gesture.

In problem solving, people also rely more on spatio-motoric information when allowed to gesture. For example, in explaining Piagetian conservation tasks, children who are allowed to gesture tend to invoke perceptual features of the tasks (such as the heights, widths, or shapes of the task objects), whereas those who are not allowed to gesture often focus on non-perceptually-present aspects of the situation, such as the initial equality of the quantities (Alibali & Kita, 2010). As a second example, when adults predict which direction a specific gear in a gear configuration will move, people who are allowed to gesture often rely on a strategy that involves simulating the movements of the gears, whereas those prohibited from gesturing are more likely to rely on an abstract strategy, based on the number of gears (e.g., if the number of gears is odd, the final gear in the row will turn in the same direction as the first gear; Alibali, Spencer, et al., 2011). Thus, gesture helps participants to generate simulations of the gears' movements. Taken together, these findings suggest that gesture activates new spatio-motoric representations, leading people to focus on spatio-motoric information in their explanations and their solution strategies.

Gesture can also activate new spatio-motoric information when people talk about abstract ideas, such as metaphors. Many metaphors are grounded in physical actions or spatial relationships (Lakoff & Johnson, 1980), and gesture facilitates the mapping between these spatio-motoric concepts and their metaphorical meanings. For example, when asked to explain the metaphorical mappings underlying phrases such as "spill the beans" (e.g., *beans* represent secrets, *spilling* represents dispersion of information), participants described the mappings for more components of the metaphor and in more detail when encouraged to gesture than when prohibited from gesturing (Argyriou & Kita, 2013; Argyriou, Mohr, & Kita, in press). Producing gestures generated spatio-motoric information based on the literal meanings (e.g., "spilling"), and facilitated participants' mappings between the literal concepts and the abstract meanings (e.g., "dispersion [of information]").

Gestures can also support abstract reasoning by activating new spatio-motoric representations that concretize or spatialize abstract ideas. For example, Beaudoin-Ryan and Goldin-Meadow (2014) asked fifth graders to judge which of two choices in moral dilemmas (e.g., cheating vs. stealing) was worse. During their responses to probe questions, children were either encouraged to gesture, prohibited from gesturing, or allowed to gesture spontaneously. Children sometimes expressed multiple perspectives in gestures, using two-handed gestures that located two individuals in different locations in gesture space, and they did so especially frequently in the gesture-encouraged condition. Crucially, children in the gesture-encouraged condition also expressed multiple perspectives most often in their speech, followed by children in the gesture-allowed group and then those in the gesture-prohibited group.[2] Thus, when multiple perspectives could be simultaneously "spatialized" in gesture, it was easier for children to incorporate multiple perspectives in their verbal statements about moral issues. Thus, activating spatio-motoric representations for abstract concepts via gesture led to a shift in participants' reasoning.

Taken together, these findings make a strong case that producing gestures activates both pre-existing and new spatio-motoric representations, which are in turn used in speaking and thinking. In this way, gesture can change the course of speaking and thinking.

Gesture Manipulates Spatio-Motoric Information

When speaking or solving problems, people often need to mentally manipulate spatio-motoric information. For example, one might need to rearrange, translate, rotate, invert, or take a new perspective on the objects one is speaking or thinking about. According to the gesture-for-conceptualization hypothesis, people can use gesture to manipulate spatio-motoric information. There are two lines of evidence for this view. The first, suggestive line of evidence shows that when manipulation is difficult, people produce more gestures. The second, more direct line of evidence indicates that producing gestures improves manipulation performance.

Difficulty in Manipulating Spatio-Motoric Information Triggers Gesture

Suggestive evidence that gesture manipulates spatio-motoric information comes from people's behavior in solving spatial transformation problems, such as mental rotation tasks (for an example, see Figure 1). People spontaneously produce gestures when they solve such problems, both when solving while talking aloud and when solving silently (Chu & Kita, 2008, 2011; Ehrlich, Levine, & Goldin-Meadow, 2006), and they gesture more when the problems are more difficult (Chu & Kita, 2011). Along similar lines, people gesture at a higher rate when describing a figure that they must mentally rotate than when describing that same figure without rotation (Hostetter, Alibali, & Bartholomew, 2011).

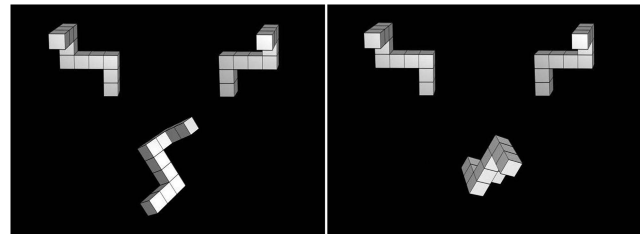

Figure 1. Two example stimuli from the mental rotation task in Chu and Kita (2011). In the left panel, the lower object was rotated from the upper left object 60° about the bisector of the horizontal and in-depth axes. In the right panel, the lower object was rotated from the upper right object 240° about the bisector of the horizontal and in-depth axes. The participant judged whether the lower object was rotated from the upper left or the upper right object.

Another source of suggestive evidence comes from people skilled at using the abacus for calculation. When calculating without an abacus, skilled abacus users often produce hand movements resembling abacus manipulation (Hatano, Miyake, & Binks, 1977), and they do so more often for more difficult problems (Brooks, Barner, Frank, & Goldin-Meadow, 2014).

Gesture Production Affects Manipulation of Spatio-Motoric Information

Studies in which the availability of gesture is manipulated experimentally provide more direct evidence that gesture functions to manipulate spatio-motoric information. Several studies have provided evidence of this sort.

Encouraging gesture promotes an aspect of spatial skill termed *penetrative thinking*, which is the ability to visualize and reason about the interior structure of object, based on observing the object's surface (Atit, Gagnier, & Shipley, 2015). Penetrative thinking requires taking a new perspective on a spatial representation; for example, geoscientists might reason about how a visible rock outcropping extends below the surface of the earth. In Atit and colleagues' study, participants were asked to explain how they would build three-dimensional versions of geologic block diagrams using playdough, and they described the resulting cross-sections. Participants who were asked to use their hands as they explained showed greater improvement on a posttest of penetrative thinking than did participants who were asked to sit on their hands while explaining. Thus, gesture improved participants' internal computation of the spatial transformations involved in creating the structures depicted in the diagrams.

Encouraging people to produce co-thought gestures improves their performance in mental rotation tasks. Chu and Kita (2011) instructed participants to solve two blocks of identical mental rotation problems while alone in a room, and without speaking. In each problem, participants judged whether the lower object was rotated from the upper left or the upper right object (see Figure 1). The availability of gesture during problem solving was manipulated in the first block of trials. Participants who were encouraged

[2] The study has three phases (pretest, manipulation, and posttest,) but here we focus on the results concerning the manipulation phase.

to gesture produced more gestures and solved more problems correctly than participants who did not receive any instructions about gesture (and who therefore produced fewer gestures) or participants who were prohibited from gesturing. Thus, gesture enhanced participants' abilities to perform spatial transformations involved in mental rotation.

In the second block, all participants were prohibited from gesturing while solving the same mental rotation problems. Participants who had been encouraged to gesture in the first block still solved more problems correctly than participants in the other conditions. Thus, gesture did not simply offload the intermediate representation of the stimulus objects in working memory to the hands—instead, gesture had a lasting impact, improving how people mentally transformed spatial information. Based on their rich experience of hand-object interaction and gestural representation of such interaction, participants could effectively simulate the rotation of an object and the visual consequences of the rotation, making the judgment more accurate.

Gesture also helps skilled abacus users to manipulate an imaginary abacus when they calculate without a physical abacus (Hatano et al., 1977). When hand movements of skilled abacus users were prohibited during mental calculation (without the abacus), they were less accurate in their calculations. These co-thought gestures helped abacus users mentally simulate abacus calculation, and prohibiting such gestures made the simulation less effective.

Taken together, experimental evidence from studies of penetrative thinking, mental rotation and abacus calculation support the view that gesture functions to manipulate spatio-motoric information.

Gesture Packages Spatio-Motoric Information

When verbally expressing complex information, a single utterance or clause is often insufficient; information may need to be distributed across multiple utterances or multiple clauses. The information has to be packaged into units that can readily be processed within a single processing cycle for speech production (Kita, 2000; Alibali, Yeo, Hostetter, & Kita, in press; termed *conceptualization* for speaking in Levelt's (1989) speech production model). In thinking and problem solving, information may need to be packaged into units for cognitive processing, as well.

According to the gesture-for-conceptualization hypothesis, gesture helps people package spatio-motoric information into units that are appropriate and useful for the task at hand. When complex information (e.g., the shape of a vase) is gesturally expressed, a single gesture may not be able to express all relevant aspects of the information, and each gesture may then focus on a particular aspect (e.g., the shape of the opening, the contour outline from a particular viewpoint). What is expressed by a gesture may be determined by affordances (Gibson, 1979) of the referent (Chu & Kita, 2016; Masson-Carro, Goudbeek, & Krahmer, 2015) or by other top-down factors (e.g., an experimental manipulation of what to express in gestures, Goldin-Meadow et al., 2009). When gesture selects a particular aspect of complex information, this information chunk can be used as a unit for utterance planning or for other forms of cognitive processing.

There are two lines of evidence that gesture helps people *package* spatio-motoric information. The first, suggestive line of evidence shows that when information packaging is difficult, people produce more gestures. The second, more direct line of evidence is that producing gestures affects how information is packaged for speaking and thinking.

Difficulty in Information Packaging Triggers Gesture

Several studies have investigated how speakers' gesture production varies when the difficulty of information packaging is manipulated. In the earliest study of this sort (Alibali, Kita, & Young, 2000), children saw one of two identical objects being physically transformed (e.g., water in a tall, thin glass poured into a shallow, wide glass), as in Piagetian conservation tasks. In the description condition, children described how the two task objects looked different. In the explanation condition, children judged whether the quantities were the same and explained that judgment. Information packaging was more difficult in the explanation task because the information expressed needed to align with the quantity judgment. Children produced verbal utterances with comparable content in the two conditions (e.g., "this one is tall, and this one is short"). However, they produced gestures that represented properties of the task objects more often in the explanation condition than in the description condition. Thus, more difficult information packaging triggered more gestures, even when the verbal utterances were comparable.

Similar effects of information packaging difficulty on gesture production have been observed in adults as well as children (Hostetter, Alibali, & Kita, 2007; Kita & Davies, 2009; Melinger & Kita, 2007). In each of these studies, participants described visually presented figures, and information packaging difficulty was manipulated by varying characteristics of the figures (see Figure 2). In each study, it was easier for participants to decide what information to encode in each utterance for easy figures than for hard figures. Across all three studies, participants produced comparable utterances for both types of figures, but they gestured more for the hard figures than for the easy figures. Thus, more challenging information packaging triggers gestures.

Gesture Production Affects Information Packaging in Speaking and Thinking

Studies in which gestures are manipulated experimentally provide more direct evidence that gesture functions to package spatio-motoric representations into units appropriate for speaking and thinking. Two studies have provided such evidence.

When the information encoded in gesture is manipulated, information packaging in the concurrent speech changes accordingly. To study this issue, Mol and Kita (2012) asked participants to describe motion events (e.g., an object rolls down the hill) that involve both manner (e.g., roll) and path (e.g., down). In the separate gesture condition, participants were told to produce a gesture that depicted manner (e.g., to rotate the hand repeatedly in one location) and a separate gesture that depicted path (e.g., to sweep the hand diagonally downward) during the description. In the conflated gesture condition, participants were told to produce a gesture that depicted manner and path simultaneously in a single movement (e.g., to move the hand diagonally downward, while rotating the hand repeatedly). Participants produced single-clause descriptions (e.g., "it rolled down the hill") more often in the conflated-gesture condition than in the separate-gesture condi-

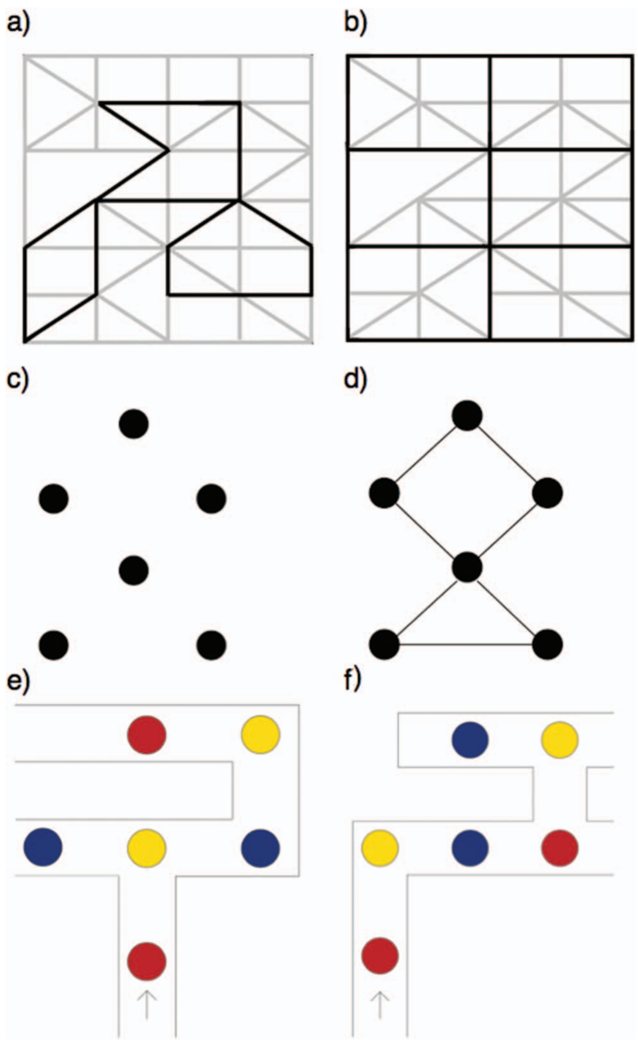

Figure 2. Stimuli from the verbal description tasks in Kita and Davies (2009; a, b), in Hostetter, Alibali, and Kita (2007; c, d), and in Melinger and Kita (2007; e, f), which manipulated difficulty of packaging information for speaking. The left panels (a, c, e) are hard stimuli and the right panels (b, d, f) are easy stimuli. For (a, b), participants described lines contained in each rectangle, ignoring the colors. In (a), the dark lines created gestalts that spanned across rectangles and made it difficult to package information within each rectangle, whereas in (b), the dark lines did not span across rectangles. For (c, d), participants described the location of the dots, ignoring any lines. In (c), participants had to package dots into verbalizable units, whereas in (d), the lines "pre-packaged" dots into verbalizable units. For (e, f), participants described a route through all circles connected by lines. In (e), participants had to decide which of two branching routes to take first, whereas in (f) the routes were deterministic. See the online article for the color version of this figure.

tion, and they produced two-clause descriptions (e.g., "it went down / as it rolled") more often in the separate-gesture condition than in the conflated-gesture condition. Thus, changing the way gestures packaged information changed how the information was packaged into clauses, which are planning units in speech production (Bock & Cutting, 1992). This finding indicates that gestural packaging of information shapes what information is encoded in each planning cycle for speech production (see also Kita & Özyürek, 2003).

One other study suggests that the content of gesture shapes information packaging for thinking. Goldin-Meadow et al. (2009) asked children to solve math equations such as 2+3+7 = _+7, and instructed them to produce gestures that encoded either a correct problem-solving strategy (a V-shaped two-finger point at 2 and 3, and then an index finger point at the blank) or a partially correct strategy (a V-shaped point at 3 and 7, and then an index finger point at the blank). At posttest, children in the correct strategy condition performed better than those in the partially correct strategy condition, and this effect was mediated by the extent to which strategies were expressed in speech at posttest. That is, gesturally expressing a particular solution strategy during the lesson helped participants to package relevant pieces of information about equations, which they verbally expressed in the posttest and used in solving the problems correctly.

Taken together, this experimental evidence supports the claim that gesture functions to package spatio-motoric information, both for speaking and for thinking.

Gesture Explores Spatio-Motoric Information

When solving a problem, one often needs to find information that leads to a solution. The challenge is to find relevant information among the many pieces of information that may or may not be useful. This challenge is similar when verbally expressing complex information; one needs to find the optimal way to encode and integrate information, from among many possibilities.

According to the gesture-for-conceptualization hypothesis, people can use gesture to explore spatio-motoric information that may be useful for the task at hand (Alibali et al., 2000; Kita, 2000). Four lines of evidence converge to build a case for this function of gesture. The first, suggestive line of evidence shows that difficult tasks trigger gestural exploration. The second, more direct line of evidence shows that people display a wider range of conceptualizations for problems when gesture is allowed than when it is prohibited, suggesting that gesture helps them to explore a wider range of options. The third line of evidence indicates that trial and error processes, which are a form of exploration, can take place in gesture. Speakers sometimes abandon gestures that they initiate, and the distribution of these abandoned gestures suggests that they are used for "trying out" ideas. The fourth line of evidence comes from qualitative case studies demonstrating how ideas develop in gestural "trial and error." Speakers sometimes try out ideas in gesture that they do not express in speech; as their utterances unfold, speakers eventually find or create a gestural representation that they then express in speech.

Difficult Tasks Trigger Exploration in Gesture

When exploring optimal ideas for solving a problem, the search is more effective when covering a wider range of ideas. Gesture can do so by "casting its net" in a different part of the conceptual space than verbal or propositional thinking (Kita, 2000). People, indeed, often express some information uniquely in gesture (i.e., not in the accompanying speech) when explaining solutions to difficult problems. Such "gesture-speech mismatches" can occur when children explain their solutions to equations such as

2+3+7 = __+7 (Perry, Church, & Goldin-Meadow, 1988). A child might express an incorrect "add all" strategy in speech ("2 plus 3 plus 7 plus 7 is 19"), and at the same time, a correct "make both sides equal" strategy in gesture (sweeping across the left side of the equation while saying "2 plus 3 plus 7", and then sweeping across the right side while saying "plus 7 is 19"; the gestures make the same movement on both sides, expressing equality). Such mismatches appear to reflect gestural exploration of information—in this case, the fact that equations have two "sides". Gesture-speech mismatches also occur when children explain Piagetian conservation tasks (Church & Goldin-Meadow, 1986) and other sorts of problem-solving tasks (e.g., Pine, Lufkin, & Messer, 2004). Children produce gesture-speech mismatches especially often when they are in a transition phase toward a more advanced understanding (Alibali & Goldin-Meadow, 1993; Church & Goldin-Meadow, 1986; Perry et al., 1988; Pine, Lufkin, & Messer, 2004). Furthermore, during transitional knowledge states, children express a wider range of solution strategies in gesture than in speech (Goldin-Meadow, Alibali, & Church, 1993), suggesting gestural exploration of solution strategies.

Speakers explore in gestures, as manifested in gesture-speech mismatches, more frequently when it is difficult for them to decide what to say. As described in the previous section, Alibali, Kita, and Young (2000) manipulated difficulty in what information to express with an explanation task (more difficult) and a description task (less difficult). Children produced more speech-gesture mismatches in the explanation task than in the description task. Thus, when it is difficult to decide exactly what information to verbally express, people use gesture to seek potentially relevant information.

Gesture Production Facilitates Exploration of Ideas

One way to measure how much information people explore is to measure the number of relevant ideas that people generate when solving problems. Studies that manipulate the availability of gesture have shown that people generate a wider range of conceptualizations when they produce gestures than when they do not. For example, Broaders and colleagues (2007) investigated whether gesturing leads to generation of more solution strategies for mathematical equations such as 2+3+7 = __+7. Children explained how they would solve such problems, first in a set of "baseline" problems in which gesture was not manipulated, and then in second set of problems in which gesture was manipulated. Relative to the baseline phase, children who were encouraged to gesture added more new solution strategies during the second set of problems than children who were prohibited from gesturing, and these new strategies were almost always expressed in gesture and not in speech. That is, gestures explored a wide range of conceptual possibilities.

Along similar lines, Kirk and Lewis (2016) investigated whether children produce more creative answers in the Alternative Uses Test (e.g., "list all nonconventional uses of newspaper", Guilford, 1967) when gesturing. When free to move their hands, the more children gestured, the greater the number of valid solutions they generated. Furthermore, encouraging children to move their hands substantially increased the number of novel uses that they generated. These findings suggest that people used gesture to explore possible affordances of the objects, and this exploration allowed them to find more solutions.

Abandoned Gestures Indicate Unsuccessful Exploration

People sometimes change their minds about their gestures and abandon them prematurely, as if exploring via trial and error in gesture. For example, when participants described their solutions to mental rotation problems (see Figure 3) in Chu and Kita (2008), they sometimes stopped their gestural movements suddenly, as if they changed their minds about what information to explore. These stoppages occurred during the stroke phase of the gesture, which is the expressive part of the movement, or during the preparation phase, in which the speaker brings the hand to the starting position for the stroke (see McNeill, 1992, and Kita, van Gijn, & van der Hulst, 1998).

If abandoned gestures are a sign of unsuccessful exploration, two predictions follow. First, these gestures should occur before gestures that reflect successful exploration, that is, nonabandoned gestures. Second, they should occur more often on hard problems than on easy ones, because people are more likely to explore possibilities on hard problems. A reanalysis of data from Experiment 1 in Chu and Kita (2008) supported both predictions.[3]

First, participants usually produced abandoned gestures prior to nonabandoned gestures within individual trials. For trials with at least one abandoned and one nonabandoned gesture, we gave a score to each gesture according to its position in the trial (e.g., for a trial with three gestures, the first gesture received a score of 1 and the third gesture received a score of 3). The mean position score for abandoned gestures ($M = 1.73$, $SD = 0.80$) was significantly lower than that for nonabandoned gestures ($M = 2.96$, $SD = 1.22$), $t(18) = -4.97$, $p < .001$, $d = -1.19$.

Second, participants produced abandoned gestures more frequently on harder mental rotation problems (i.e., 120° and 240° rotation angles; $M = 0.92$ per minute, $SD = 0.98$) than on easier problems (i.e., 60° and 300° rotation angles; $M = 0.57$ per minute, $SD = 0.60$), $t(18) = -2.58$, $p = .019$, $d = 0.43$. Thus, task difficulty elicits gestural exploration of information. Further analyses excluded the possibility that these abandoned gestures were a consequence of abandoned speech, in which participants corrected or repeated their own speech (for these analyses, see the supplemental material).

Microgenesis of New Ideas in Gesture

If gesture functions to explore spatio-motoric information, as we suggest, this should be reflected in the microgenesis of ideas in gestures. That is, trial and error processes should be evident in gesture as speakers generate utterances or approaches to solving problems, and these processes should sometimes lead to ideas that are expressed in speech or offered as problem solutions. Here we discuss two examples in which gestures explore various related ideas, until eventually the speaker finds an idea that is appropriate for the task.

The first example (see Figure 4) comes from a speaker narrating an animated cartoon she had just seen (data from McNeill, 1992). She is

[3] This study was conducted under the ethical approval for the project "Spontaneous gesture" (Reference number 181005153), granted by the University of Bristol Department of Experimental Psychology Human Research Ethics Committee.

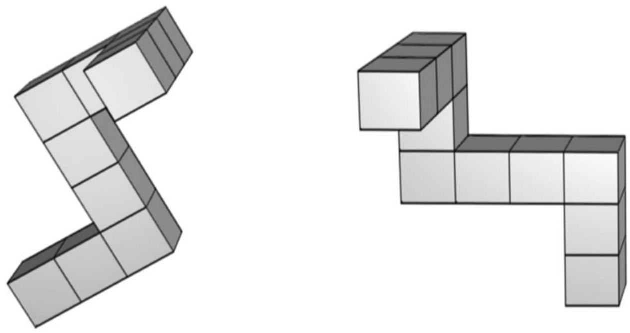

Figure 3. A stimulus used in the Experiment 1 of Chu and Kita (2008). The left object was rotated 60° anti-clockwise about the in-depth axis. Participants' task was to describe how the left three-dimensional object could be rotated to the position of the right one (e.g., "Rotate it anti-clockwise about the in-depth axis for about 60°").

describing a scene in which Sylvester (a cat) is running away as he holds Tweety (a bird) in his hand, but a heavy weight, which had been catapulted up in the air earlier, comes down on him and crushes him. This crushing is important as it allows the story to move forward; it makes Sylvester release Tweety, and she escapes.

In this example, the speaker explores different ways of packaging the crucial information—initially representing multiple aspects of the event (the weight flying through the air and the weight hitting the cat), and eventually zeroing in on the hitting event, which is most crucial to the story line. Her first gesture (Figure 4, left panel) depicts both the weight (represented by the left hand) flying through the air in an arc trajectory and the weight hitting the cat (represented by the right hand). She just says "uh uhm" while producing this gesture, presumably because the depicted information was too complex to be verbally expressed in a single clause. In the second gesture (right panel), she "recycled" the final part of the first gesture, and depicted solely the hitting event. This time, she produced a full-fledged verbal description: "he gets clobbered by the weight." Her two gestures explored different ways to conceptualize the scene. It appears that a relatively small change in the gestural representation led her to focus on the crucial hitting event, allowing the discourse to move forward.

As a second example, consider a boy explaining his judgment to a Piagetian task in which the experimenter poured one of two identical, tall glasses of sand into a short, wide dish (Figure 5;

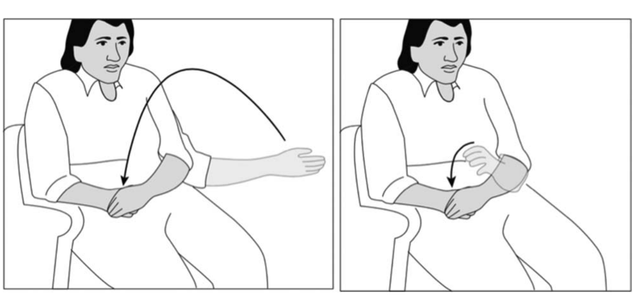

Figure 4. Gestural exploration of information during narrative (example from the recording analyzed in McNeill, 1992). The accompanying speech was, "uh uhm (left panel), he gets clobbered by the weight (right panel)".

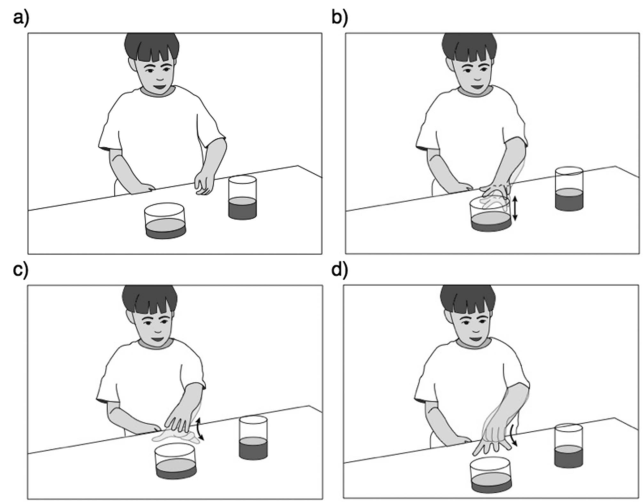

Figure 5. Gestural exploration of information during problem solving (example from the dataset reported in Alibali et al., 2000). The accompanying speech was (a) "cause um . . .", (b) "the bowl is wi-, cause the bowl is," (c) "wider", (d) "it needs to fill out".

example from the dataset described in Alibali et al., 2000). The boy claimed that the tall glass now contained more sand than the short dish. In explaining this judgment, he began by saying "Cause, um . . ." and pointed toward the taller glass (Figure 5, Panel a). However, he quickly abandoned this thought about the tall glass, and shifted his attention to the short dish, saying, "the bowl is wi- —cause the bowl is wider." With this utterance, he made a V-shaped gesture with the index and middle fingers of his left hand, and moved it down and up repeatedly at the side of the dish, representing its width and height (Figure 5, Panel b). As he completed this utterance, while saying the word "wider", he moved his hand into a claw shape over the dish, and spread and closed his fingers (twice), representing the area of the top of the dish (Figure 5, Panel c). Notably, the idea of spreading or area that he expressed in this gesture goes beyond the notion of width which he said in the accompanying speech. He then pulled his hand back into a point toward the dish and ultimately back to his body while saying "and it needs um. . . ." He then concluded, "it needs to fill out." With this final utterance, he repeated the spreading gesture, with his hand again moving from a claw shape to a flat hand with fingers spread (Figure 5, Panel d). With this gesture he depicted the sand "filling out" a wider area, which occurred when the experimenter poured the sand from the glass to the dish.

In this example, the boy explored many features of the task objects in gesture; he (eventually) lexicalized many, but not all, of these features. At the outset, he seemed to explore the possibility of saying something about the tall glass, but quickly decided against it. He then explored the width and height of the dish, with the up-and-down V gesture at the side of the dish. He eventually lexicalized the feature "wider", but did not ever (in the course of this explanation) lexicalize height (thus producing a gesture-speech mismatch). Finally, he explored the area of the dish and the spreading of the sand, using a spreading gesture over the dish. He repeated this gesture a total of three times, eventually lexicalizing it using the verb "fill out", on the third iteration of the gesture.

Most relevant to our point here, many of the features that he eventually lexicalized were expressed first in gestures, and only later in speech. We suggest that his gestural exploration of the task objects helped him generate the idea that the sand fills out a larger area in the dish than in the glass.

Of course, in both of these examples, one cannot infer that the change in gesture caused the change in the speaker's focus; it remains possible that the gestures simply reflect rather than caused that change. Nevertheless, these examples are important in illustrating how gestural exploration can unfold over time and can influence verbally expressed conceptualizations of events or objects.

Summary of the Evidence for the Exploration Function

In summary, several lines of evidence converge to suggest that gesture explores information that may be useful for speaking and thinking. The most direct evidence comes from studies that manipulated gesturing and showed when people gesture, they have access to a wider range of ideas (Broaders et al., 2007; Kirk & Lewis, 2016). Gestural exploration of ideas is manifested in gesture-speech mismatches, in abandoned gestures, and in gestural discovery of novel ideas that are subsequently expressed in speech. The key features of these phenomena are that the microgenesis of ideas in gesture is, to some extent, independent from (and blazing the trail for) the microgenesis of ideas in speech, and that ideas develop in gesture via a process of trial and error (see Goldin-Meadow, Alibali, & Church, 1993; abandoned gestures in reanalysis of Chu & Kita, 2008). When people use gestural, spatio-motoric thinking and verbal, propositional thinking in parallel, they cast a wider net for possible solutions (Kita, 2000). Engaging multiple qualitatively different ways of thinking enriches the conceptual resources that come into play. This argument is based on growth point theory (McNeill, 1992), which proposes that the interplay of two qualitatively different kinds of thinking—gestural thinking and verbal thinking—drives the speaker's cognitive processes forward because more diverse ways of conceptualizing information or framing the problem become available.

Relationship Among the Four Functions

We argue that the four proposed functions are distinct from one another; however, they can also work together to enhance performance. The four functions can operate simultaneously; for example, when a speaker talks and gestures about an object that is no longer present, a gesture may both activate and explore spatio-motoric information about the object at the same time. Furthermore, the exploration function may be triggered by the need for better packaging of information or by the need to manipulate spatio-motoric information (e.g., to describe something from the listener's perspective).

We argue that all four functions may operate every time people produce gestures. However, the dominant function at any given moment may depend on what is required for the task at hand. For example, gesture may be used to explore when novel conceptualizations are useful (Kita, 2000)—and gestures that manifest this exploration are most frequent when conceptual exploration is useful. In support of this claim, several studies have shown that children produce gesture-speech mismatches most frequently when they are at the cusp of understanding a task (Church & Goldin-Meadow, 1986; Perry et al., 1988; Pine et al., 2004).

Gestures Are Generated From the Same System That Generates Practical Action

Why can gesture activate, manipulate, package, and explore spatio-motoric information? In addressing this question, we consider the mechanism that gives rise to gesture, and its implications for our arguments about gesture function. We argue that gesture has these functions because it has roots in practical action. For each gesture that indicates body movement, object shape, object movement or object location, there is a similar practical action. For example, a gesture that depicts holding a mug to drink is similar to grasping a mug to drink, a gesture indicating the round shape of the rim of a mug is similar to tracing the rim of a mug, a gesture that tracks the path of a ball is similar to tracking the movement of a ball by changing the direction of gaze, a pointing gesture to an object location is similar to reaching for an object, and so forth.

Practical actions can also serve the four functions that we posited for gestures: activating, manipulating, packaging, and exploring spatio-motoric information. When planning an action in a physical or virtual (imagined or simulated) environment, one needs to take into account spatial information in the environment; for example, when the hand reaches out to grasp a mug, the location of the mug determines the trajectory of the hand and the shape and orientation of the mug afford certain possibilities for grasping (Gibson, 1979). In this sense, practical actions can activate spatio-motoric information (see Casasanto & Dijkstra, 2010, for experimental evidence). The hand can grasp and manipulate an object to examine perceptual consequences of the object's movement; as one example, manipulating a mug can help one visualize it from different angles. When the hand interacts with an object, only certain features of the object are relevant; for example, when grasping the handle of a mug, only the size and orientation of the handle are relevant, and when tracing the rim of a mug, only the circular shape and size of the opening are relevant. In this sense, practical actions can package information about an object. The hand can also explore various possibilities for manually interacting with an object; for example, a hand may try out various ways to interact with a mug. Thus, practical actions and gestures serve similar functions.

It is sometimes difficult to draw a line between practical action and gesture when the hand interacts with an object for communication (see also Novack & Goldin-Meadow, 2016). For example, one may demonstrate how to use a tool by producing movements with the tool that simulate using the tool (Clark, 1996; LeBaron & Streeck, 2000; Streeck, 1996) or one may show how to move or use an object by producing an empty-handed action near the object (Novack, Wakefield, & Goldin-Meadow, 2016). Some researchers have distinguished between gestures and practical actions or "functional acts", such as picking up or manipulating an object (Goldin-Meadow, 2003). In contrast, other researchers have argued that gestures and practical actions are functionally similar. For example, in their analyses of teachers' gestures, Alibali, Nathan, and Fuijmori (2011) argued that "hold up" gestures (i.e., gestures that display objects by holding them up) are functionally similar to deictic gestures because they indicate specific referents by bringing those referents into a space where the recipient is likely to attend (Clark, 2003). They further argued that "hold-up-plus-action" gestures (i.e., gestures that involve holding up and manipulating objects) are functionally similar to representational gestures because they depict meaning through action. To illustrate, one of the teachers in their sample was giving a lesson about calculating the area of a triangle; as part of this lesson, the teacher held up two identical paper triangles and moved them together to illustrate that two triangles form a rectangle (see Figure 6).

Practical actions produced during thinking have gesture-like properties when the hand interacts with objects for reasoning and thinking, as well as for communication. Consider an example from the study, described above, in which children were asked to describe the task objects used in Piagetian conservation tasks (Alibali et al., 2000). In one task, children were shown two identical balls of playdough, and then the experimenter flattened one ball into a disk. In describing the task objects, one child said, "One's round," while rolling the unchanged ball around on the table. In this example, the child's rolling action expressed a physical property of the ball—its spherical shape—by actually manipulating the ball. Along with this action, the child expressed the spherical shape in speech with the word "round." The child then continued by saying, "and one's flat," and indicated the flattened disk with a flat palm gesture facing down over the disk, in this case, without manipulating the playdough. Thus, in this part of the utterance, the child used a gesture that represented an aspect of the object, but did not manipulate the object. In this example, object manipulation and gesture were used in parallel parts of the same utterance, suggesting that they are similar in a fundamental way.

Some theoretical accounts of co-speech gesture production have proposed that gestures are generated by the same cognitive processes that also generate practical actions. According to the information packaging hypothesis, "what underlies a gesture is an action in virtual [imagined] environment" (Kita, 2000, p. 170).

Figure 6. A "hold-up-plus-action" gesture in which the speaker manipulates an object (example from the recordings analyzed by Alibali, Nathan, & Fujimori, 2011).

Similarly, the interface hypothesis (Kita, 2014; Kita & Özyürek, 2003) proposes that gestures are generated from a general-purpose "action generator," which determines the content of both practical actions and representational actions, that is, gestures. The gesture as simulated action framework (Hostetter & Alibali, 2008) holds that the mental representations that underlie gestures are simulated actions and perceptual states. In addition to these theories about co-speech gestures, the action generation hypothesis (Chu & Kita, 2016) extends the same action-based view to co-thought gestures. These theories contrast with theories that embed gesture generation solely within speech production processes (Butterworth & Hadar, 1989; de Ruiter, 2000; McNeill, 1992).

The gesture-for-conceptualization hypothesis builds on the idea that gestures are generated from the same process that generates practical actions (cf. Chu & Kita, 2016; Hostetter & Alibali, 2008; Kita, 2000; Kita & Özyürek, 2003). That is, the information encoded in gestures is generated from the action system.

What is the evidence for this link between practical actions and gestures? There are three primary lines of evidence. First, people produce more gestures when they think or speak about motoric content than when they think or speak about other content, because thinking and speaking about such content presumably involves simulating actions or movements in space. Indeed, people produce more co-speech gestures when they talk about motor imagery (e.g., explain how to wrap a present) than when they talk about visual imagery (e.g., describe your favorite painting) or about abstract information (e.g., express your view on the use of a single currency in Europe; Feyereisen & Havard, 1999). Furthermore, in object description tasks, people produce more co-speech gestures when they describe objects that are highly manipulable, such as a stapler, than when they describe objects that people do not typically manipulate with their hands, such as a fence (Hostetter, 2014; Masson-Carro et al., 2015; Pine, Gurney, & Fletcher, 2010). This pattern holds, even when controlling for the objects' spatiality, concreteness, and ability for self-produced movement (Hostetter, 2014). Moreover, when people describe manipulable objects, they tend to produce gestures that depict the physical actions involved in using or handling those objects (Masson-Carro et al., 2015).

Second, when talking about objects, gesture rates are also sensitive to variations in the affordances of objects, even when the content of speech does not vary with these affordances. Chu and Kita (2016) presented participants with two images of a mug, and described how one mug could be rotated into the position of the other. The mugs either had smooth surfaces or had spikes on their surfaces (see Figure 7). Participants produced more co-speech gestures on the smooth mug trials than on the spiky mug trials, even though the spikes were irrelevant to the task goal and thus had no impact on the content of speech. The same effect of varying affordances was found in co-thought gestures when participants silently performed a mental rotation task with either smooth mugs or spiky mugs as the stimulus objects (see Figure 8). Thus, gestures were affected by the affordances of the stimulus objects in the same way that practical actions would be affected.

Third, experience with physically manipulating objects influences speakers' gestures. Hostetter and Alibali (2010) examined the gestures people produced when they described information (the dot and line patterns in Figure 2c) that they had acquired either visually or through physical action. Participants who constructed the patterns manually (using wooden disks)—who would therefore

Figure 7. Two stimulus displays used to elicit co-speech gestures (Chu & Kita, 2016): The smooth condition (left panel) and the spiky condition (right panel). The mugs in the left panel were highly graspable, whereas the mugs in the right panel were less graspable. Participants' task was to describe the rotation of the mug (e.g., "The mug on the left side of the screen was rotated 60° backwards around the horizontal axis"). See the online article for the color version of this figure.

be expected to simulate action more strongly—produced more co-speech gestures than participants who simply viewed the patterns.

Gestures about actions reflect features of the action that the speaker has performed. Cook and Tanenhaus (2009) asked participants to solve Tower of Hanoi problems (Newell & Simon, 1972), which involve lifting disks off pegs and moving them to other pegs. Participants in a physical action group solved the problems with real objects, actually lifting and moving disks. Participants in a computer action group solved the same problems on a computer screen, dragging disks with the mouse from one peg to another. When participants verbally reported how they had solved the problems, those in the physical action group produced more co-speech gestures with grasping hand shapes. In addition, the motion trajectories of their gestures were more curved than those of speakers in the computer action group. Thus, gesture reflected features of the actions that participants had actually performed.

If gestures are generated from the same system that generates practical action, how can we account for the fact that the contents of speech and gesture are highly coordinated (McNeill, 1992)? We argue that this occurs because the action generation system and the speech production system are highly interactive. As proposed by Kita and Özyürek (2003), the two systems can exchange information and align their contents. Thus, the contents of concurrent gesture and speech tend to converge.

Our hypothesis can also explain cases in which the contents of speech and gesture are not fully aligned. In some cases, speakers provide more specific information in gesture than in speech. For example, a speaker might produce a swiping gesture while saying "cleaning the room". In other cases, speakers express information in gestures that they do not express at all in the accompanying speech. As one example, the boy in Figure 5 indicated the taller glass in gesture (Panel a), and also depicted the height of the shorter dish in gesture (Panel b), but he never expressed these pieces of information in his spoken explanation. When it is advantageous for gesture to explore information possibly relevant to the task at hand, the pressure to semantically align speech and gesture may be relaxed, and speakers may produce gestures that are not redundant with speech (Kita, 2000). Thus, our framework, in which speech and gesture are generated interactively in separate processes, is compatible with both semantic integration of speech and gesture (e.g., Kita & Özyürek, 2003; McNeill, 1992), and systematic weakening of this integration (e.g., Church & Goldin-Meadow, 1986).

Gesture Goes Beyond Practical Action by Schematizing Information

Although gestures are closely linked to actions, there is a critical difference between gesture and action: namely, gestures are representational. Gestures represent the world; in most cases, they do not influence, alter, or directly affect the physical world (Novack & Goldin-Meadow, 2016). Thus, gestures are somewhat "removed" from action—they schematize actions, rather than represent actions veridically (see Annett, 1990).

Because gestures are representational, one might expect that gestures would have less influence on thought than actions. However, evidence to date points in the opposite direction: gestures have a more powerful influence on thought than actions do.

We argue that gesture's powerful influence on thought is a consequence of its ability to schematize. This schematization is a form of abstraction—that is, it strips away some elements, while maintaining others. In this section, we first present evidence that gestures affect thought more strongly than actions do. We then make the case that these effects are due to gesture's ability to schematize information. We then discuss how gestural schematization shapes the four functions of gesture.

Gestures Affect Thought More Strongly Than Actions Do

Four lines of evidence converge on the conclusion that gesture can affect thinking more strongly than actions. First, gesture has a stronger influence on solvers' representations of problems than action does. Beilock and Goldin-Meadow (2010) asked participants to solve Tower of Hanoi problems with real disks and to explain their solutions. During the explanation phase, participants either verbally explained their solutions with gestures (the gesture group) or physically moved the disks to illustrate their solutions (the action group). All participants later solved Tower of Hanoi problems with real objects again, with half of the participants in each group using the original set of disks (the no-switch condition) and the other half using disks whose weights had been switched so that the smallest disk was heaviest and the largest disk was lightest (the switch condition). The weight change affected how people's

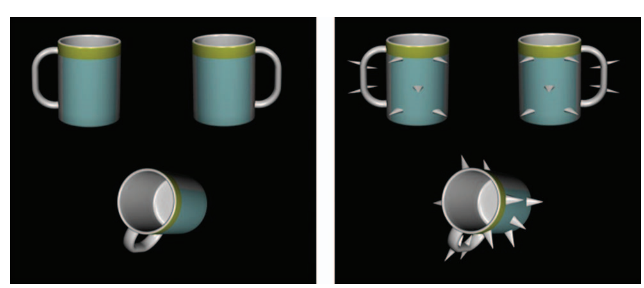

Figure 8. Two stimulus displays used to elicit co-thought gestures (Chu & Kita, 2016): The smooth condition (left panel) and the spiky condition (right panel). Participants' task was to judge silently whether the lower mug was rotated from the upper left or the upper right mug. In this example, the lower mugs were rotated from the upper left object 60° around the bisector of the horizontal and vertical axes. Note that only one side of the mugs was painted blue, and the blue patch does not go all the way around the mugs. See the online article for the color version of this figure.

hands were involved in the solution: the heaviest disk had to be moved using two hands, whereas the lightest could be moved using one hand. Participants in the action group were not affected by the weight switch; their solution times were similar in the two conditions. In contrast, participants in the gesture group took longer to solve the problem in the switch condition than in the no-switch condition. This finding suggests that gesturing about actions exerted a stronger influence on how action-relevant information was mentally represented than actually performing the actions. Put another way, weight information was incorporated into the schematized spatio-motor representations (one-handed vs. two-handed movement) that participants constructed in the gesture condition, so the shift in weight was more problematic for them.

Second, gesture facilitates encoding of spatial information more so than practical actions do. So, Ching, Lim, Cheng, and Ip (2014) familiarized participants with a diagram showing a spatial route. They then removed the diagram and asked participants either to rehearse the route with hand gestures in the air (the gesture group), to draw the route on a piece of paper (the action group), to mentally visualize the route without moving their hands (the mental-simulation group), or to read aloud some random letters (the no-rehearse group). All participants were then asked to recall the route verbally. Participants in the gesture group recalled more steps correctly than did participants in the action group (and those in the gesture and action groups did better than those in the other two groups). These results suggest that producing gestures was beneficial for participants' encoding of critical spatial information about the routes. Put another way, gesture schematized key information from the routes, leading to robust and durable memory for that information.

Third, gestures have been found to facilitate generalization of mathematical strategies more than actions do. Novack and colleagues (2014) presented children with mathematical equations (e.g., 2+9+4 = __+4) on a white board, with the numbers covered by matching number magnets. All of the children were then asked to repeat the explanation, provided by the experimenter, that both sides of the equation needed to be equal. Along with this speech, children were asked to produce actions or gestures. In the action condition, children were asked to pick up the magnetized numbers 2 and 9 from the left side and move them into the blank on the right side. In two gesture conditions, children were asked either to mimic the actions described in the action group but without physically moving the numbers (termed a "concrete gesture"), or to point with the fingers of one hand to the two digits on the left side and then point to the answer blank (termed an "abstract gesture"). In a subsequent test phase, children in both gesture conditions performed better than those in the action condition in solving equations with a different structure (i.e., with the blank in a different position). Further, children in the abstract-gesture condition performed better than those in the other conditions in solving equations without a repeated addend (e.g., 2+5+3 = __+6). Thus, children who produced gestures were more successful than children who performed actions in generalizing the knowledge they gained in the training phase to solve structurally different problems, and the benefits were greatest for those children whose gestures were more schematic. Novack and colleagues concluded that gestures promoted a deeper understanding of mathematical equivalence by focusing attention on relevant aspects of the equations and abstracting away from irrelevant aspects.

Fourth, abacus experts can calculate faster without an abacus than with a physical abacus, and their calculation is less accurate if they are prohibited from gesturing when they calculate without an abacus (Hatano et al., 1977). Thus, gestures allow abacus experts to use schematized spatio-motoric information for efficient and accurate calculation. Calculation is slower with a physical abacus because the physical objects impose constraints that are not relevant to computation (e.g., beads need to move a particular distance).

To summarize, gesture can affect cognition more strongly than practical actions. Gesture can leave a stronger memory trace than physical action, both for properties of manipulated objects (Beilock & Goldin-Meadow, 2010) and for visually presented routes (So et al., 2014). Furthermore, gesture promotes learning of problem-solving strategies that are generalizable to new situations, more so than practical actions (Novack et al., 2014). In some cases, gesture also manipulates spatial representations (e.g., for abacus calculation) more efficiently than practical actions (Hatano et al., 1977).

Key Differences Between Action and Gesture

There are several key differences between practical action and gesture. First, gesture is always representational (it stands for something else; Novack & Goldin-Meadow, 2016), but action is not always so. On this basis, gesture may influence other representations, such as verbal thought, spatial memory, and problem-solving strategies, more strongly than action (see, e.g., Novack et al., 2014; So et al., 2014). Second, gesture is usually free from the physical constraints that practical actions are subject to. This makes gesture more flexible than action in what it represents and how it represents than action. Third, gesture usually does not leave a physical trace, but practical action often does. Physical traces may help reduce working memory load, but they may also constrain how malleable the representation is. Finally, and most crucially, gesture schematizes information. We argue that schematization affects mental representations in specific ways that shape the four functions, and we discuss this issue in the following section.

Why Do Gestures Affect Thought More Than Actions?

Why does gesture exert a more powerful influence on thought than action itself? One possibility, proposed by Goldin-Meadow and Beilock (2010), is that gestures are not tied to real objects, as actions are. According to this view, when gesturing, people cannot rely on the affordances of the objects to direct their gestures; they must instead actively create and maintain spatio-motoric representations of objects in their working memory. In contrast, when people act on real objects, the sensorimotor details required for action can be embedded in or off-loaded to the environment. Therefore, relative to actions, gesture forces people to create richer internal representations of the objects and to build stronger links between body movements and thinking. This account can explain why, in the Tower of Hanoi task, gesturing leads people to represent the weights of the disks, which are not relevant to the task, more strongly than producing the actions does (Beilock & Goldin-

Meadow, 2010; see also So et al., 2014 for a similar view). However, it is difficult for this account to explain gesture's advantage in generalizing strategies (Novack et al., 2014).

To explain gesture's advantage over practical action, we argue that gestures enrich thinking via a process of schematization. Schematization involves deleting or stripping away some elements of a representation, and maintaining others. Gesture schematizes actions and perceptual states, and this schematization facilitates cognitive processing in three main ways.

First, as Goldin-Meadow (2015) has argued, schematization facilitates generalizing knowledge to new contexts. This occurs because schematic gestural representations omit concrete details of actions and action-related features of objects. In this way, schematization helps people focus attention on essential elements, and neglect irrelevant details that are tied to specific actions or objects (Novack & Goldin-Meadow, 2016). This schematization makes it easier to transfer the represented information to new contexts (Novack et al., 2014).

Second, schematization makes processing of task-relevant information more efficient. Schematized information is "light-weight" and free from physical constraints. This makes it more efficient to use the representations, as indicated by studies of route memory (So et al., 2014) and mental abacus (Hatano et al., 1977).

Third, schematization allows representations to be flexible and open to change. Schematized representations can be adjusted to become leaner or richer, as suited to the task or context at hand. This modifiability is partially a consequence of schematized information being light-weight and free from physical constraints. Evidence for this characteristic comes from a study of the microgenesis of co-thought gestures during mental rotation (Chu & Kita, 2008). This study showed that the contents of co-thought and co-speech gestures themselves changed over trials: gestures shed task-irrelevant information and became less physically bound to the visual stimuli as participants gained more experience with the task. A similar pattern has also been observed in gear movement prediction problems (Schwartz & Black, 1996) and in the qualitative analysis of the microgenesis of ideas in gestures presented in Figure 4. The speaker's gestural representation of the cartoon scene evolved from one that contained too much information for felicitous verbalization, to one with an appropriate amount of information for verbalization.

Schematized gestural representations can also be elaborated, as needed for the task at hand. For example, when solving gear movement prediction problems, people often have difficulty understanding that a gear system with an odd number of gears arranged in a circle will not move, because the gears will "jam" (Spencer, 2003). When people fail on problems with configurations that jam, they sometimes enrich their gestural representations of the problems, adding more details about the gears' movements, in order to reason through how the gears will move. Because gestural representations are flexible and modifiable, they can be adapted to be richer or leaner, depending on the solver's needs at that moment in time.

When considering the consequences of schematization, it is important to consider what information gesture sheds and what information it retains. There is no evidence, to date, that gesture "intelligently" selects information useful for the task goal (unless participants are asked to imitate a gesture that is designed to do so, as in Novack et al., 2014, and Goldin-Meadow et al., 2009). Indeed, gesture sometimes retains information that is not useful for the task goal. For example, when telling a story based on an animated cartoon, speakers commonly produce gestures that depict motion events in the cartoon. Speakers reproduce the left-right direction of motion with high accuracy in gesture (e.g., when depicting a protagonist moving to the left in the cartoon, speakers tend to make gestures that move to their left), even though speakers never linguistically encode left-right direction in this description task, because it is not relevant to the story (Kita & Özyürek, 2003). Thus, basic parameters of visual experience may be retained in gesture, even when they are irrelevant to the task goal, because the gesturing hand has to move in space. Similarly, basic parameters of actions on objects that are irrelevant to the task goal may be retained in gestures (e.g., whether a disk was moved with one hand or two hands in the Tower of Hanoi task; Beilock & Goldin-Meadow, 2010). In general, gestural schematization reduces information, but it may also retain some spatio-motoric information that is not relevant or useful for the task at hand.

Gestures schematize information in specific ways; thus, the extent to which gestural schematization is useful for a given task depends on the match between the nature of that schematization and task goals. For example, gestures may schematize the movement of an object in three ways: (a) tracing the trajectory with a point, (b) by moving the hand along the trajectory with a handshape that represents some aspects of the object or the surface (which supports the object), and (c) the hand depicting grasping of the object (Chu & Kita, 2008; Sekine, Wood & Kita, 2016). Gestures may schematize an object also in three ways: (a) tracing its outline, (b) moving the hands as if to touch (sculpt) the object surfaces, and (c) using handshape to represent the shape (e.g., a flat hand to represent a flat object; Masson-Carro et al., 2015; Müller, 1998). Focusing only on the trajectory of object movement and abstracting away the object shape may be useful when describing rotation of the object, as in Figure 3. However, if the task depends crucially on the details of the shape of a moving object (e.g., in the game, Tetris), such schematization may not be helpful. In fact, it is not easy for a gesture to represent both the movement and shape of an object in detail at the same time. Thus, the benefits of gesture may be limited for tasks that require both details of movement and details of shape. More generally, the benefits of gesture may be especially large when the way gestures schematize information happens to be useful for the task at hand.

How Schematization Shapes the Four Functions of Gestures

The schematic nature of gestural representation shapes the four basic functions of gesture in particular ways. In all cases, information reduction plays a key role.

First, let us consider the role of schematization in the activation of spatio-motoric information. When thinking about a stimulus or an event, there are often many different sorts of information one could focus on, and one must, by necessity, focus on some aspects and neglect others. In this sense, encoding inherently involves some form of schematization or stripping away of details. We argue that producing gestures helps maintain spatio-motoric information, rather than non-spatio-motoric information, in encoding of stimuli and events, because gesture involves movement in space. For example, when allowed to gesture in solving a gear movement prediction task, people focus more on the movements of the gears (a spatio-motoric aspect of the stimulus) than on the number of gears in the array (a non spatio-motoric aspect of the stimulus, Alibali, Spencer, et al., 2011). We argue that the action of producing gesture may lend additional activation to spatio-motoric aspects of a representation of a stimulus or event, or it may actually create new spatio-motoric representations, de novo. This puts a focus on spatio-motoric aspects of situations, stripping away other aspects.

Next, let us consider manipulating spatio-motoric information. Manipulating images or ideas (, e.g., rotating, altering, inverting, or taking a different perspective) requires one to zero in on and analyze the spatio-motoric information that is relevant to that transformation, and schematization via gesture enables this focus and analysis. In addition, manipulating information places a heavy load on working memory, especially if one must keep track of every detail. If an image or idea is schematized into a more "light-weight", less complex, more stripped-down representation, it will require less working memory to manipulate (see Koedinger, Alibali, & Nathan, 2008, for discussion of this issue). Thus, gesture facilitates the manipulation of ideas because schematization via gesture reduces the amount of information to be processed.

For the same reason, schematization is also relevant to packaging spatio-motoric information into units for speaking. Not all of the elements of complex visuospatial events, scenes, or objects can be simultaneously captured in a single utterance or in a single step in a reasoning process; instead, one must focus on an appropriate, relevant subset of elements at a time—specifically, a subset that is suitable for speaking or thinking. Thus, in the same way that a schematized representation is more suitable for mental manipulation than a richly detailed representation, a schematized representation is more suitable for packaging into units or chunks for speaking or thinking.

Finally, schematization is also involved in exploring the space of possibilities for speaking or thinking. People use gesture to explore different ways of conceptualizing a situation. Because gesture schematizes information, this search is efficient and effective. That is, schematization via gesture reduces the amount of information being considered at any given moment. This "distilled" information can be more easily focused on and evaluated for its relevance to the current goal. For example, in thinking about a conservation of liquid quantity task, a child faces a rich array of sensory information about the task objects, from which gesture might schematize the heights of the containers, the widths of the containers, the pouring of the liquid, or any of a number of other features. Each of these features may be relevant for making a judgment and providing an explanation. Producing gestures can help to convert this rich array of information into a unique landscape of possible schematizations; exploring these schematized possibilities is efficient and may readily lead to novel ideas and solutions. For example, the child in Figure 5 seems to have generated the notion of area in gesture, and he eventually focused on this schematization of the task object in his verbal explanation.

Discussion

Summary of the Claims

We have considered how co-speech and co-thought representational gestures influence gesturers' mental representations and processes in speaking and thinking. We proposed the gesture-for-conceptualization hypothesis. First, representational gesture—including both co-speech and co-thought gesture—shapes the ways we conceptualize information through four basic functions: gesture activates, manipulates, packages, and explores spatio-motoric information for the purposes of speaking and thinking. Second, the schematic nature of gestural representation shapes these four functions. By schematizing spatio-motoric information for these four functions, gesture facilitates cognitive processing and generates novel ideas, strategies and solutions that are easy to process, adaptable, and generalizable.

To understand these functions of gesture, it is important to consider how gesture is related to practical actions. We take the position that representational gestures are generated by the same process that also generates practical actions (Kita, 2000; Kita & Özyürek, 2003). That is, gesture is a representational use of the action generation system (see also Chu & Kita, 2016; Hostetter & Alibali, 2008; Hostetter & Boncoddo, in press; Novack & Goldin-Meadow, 2016). Because gesture originates in the action system, gesture can influence thoughts about spatio-motoric information, based on our bodily experiences in perceiving and interacting with the world, and about abstract information, via the metaphorical use of spatio-motoric information. However, gesture differs from practical actions in an important way: Gestures are *schematic representations* (Chu & Kita, 2008; de Ruiter, 2000; Novack et al., 2014). Because of schematization, gestural representations (a) focus on essentials and neglect specific details, which facilitates generalization to new contexts (Goldin-Meadow, 2015), (b) can be processed efficiently, because representations are light-weight and are not bound to physical constraints, and (c) are flexible and modifiable, and therefore easy to adapt to the current goal. These features of gestural schematization make the activation, manipulation, packaging and exploration processes more effective and efficient. That is, schematization via gesture focuses on spatio-motoric information, stripping away other types of information (activation), makes it possible to efficiently modify representations (manipulation), focuses on small chunks of spatio-motoric information appropriate for speaking and thinking (packaging), and creates a unique landscape in which information can be explored (exploration).

Relations to Other Theories of Gesture Production

The gesture-for-conceptualization hypothesis is based on the assumption that gesture originates from a general-purpose action generator. This assumption aligns with claims made in a number of previous theoretical proposals (e.g., Hostetter & Alibali, 2008; Kita, 2000, 2014; Kita & Özyürek, 2003) and in empirical work (e.g., Chu & Kita, 2016; Cook & Tanenhaus, 2009; Feyereisen & Havard, 1999; Hostetter, 2014; Hostetter & Alibali, 2010; Pine et al., 2010). This view contrasts with theoretical proposals that assume that co-speech gesture originates from a subprocess of speech production (e.g., Butterworth & Hadar, 1989; McNeill, 1992).

The gesture-for-conceptualization hypothesis goes beyond previous accounts of the self-oriented functions of gestures in important ways. The hypothesis unifies disparate existing accounts of how gesture affects speaking. Furthermore, it provides a unified account for how gesture influences both speaking and thinking, with special attention paid to co-thought gesture. Moreover, it proposes four functions for both co-speech and co-thought gestures, and it specifies how gestural schematization of information shapes these four functions. Thus, the proposed framework provides a novel, parsimonious and comprehensive theory of the self-oriented functions of gestures. In this section, we illustrate how the proposed four functions relate to existing proposals on self-oriented functions of gestures.

The gesture-for-conceptualization hypothesis proposes that gesture activates spatio-motoric information. This function relates to two existing accounts of the self-oriented functions of co-speech gestures. First, some researchers have argued that co-speech gestures maintain imagery during linguistic encoding (de Ruiter, 1998; Wesp et al., 2001). The activation function in the current proposal essentially encompasses the image maintenance hypothesis, in that the image maintenance function is narrower than the activation function. According to the image maintenance hypothesis, gesture simply boosts the activation of pre-existing imagery. In contrast, the activation function in the gesture-for-conceptualization hypothesis allows gesture both to boost activation of pre-existing spatio-motoric representations and to generate spatio-motoric representations that would not have existed otherwise (see Hostetter & Boncoddo, in press, for a similar view). That is, gesture can change the content of thought by generating new spatio-motoric representations.

Second, some researchers have argued that co-speech gestures facilitate the retrieval of words from the mental lexicon (Hadar & Butterworth, 1997; Krauss et al., 2000; Rauscher et al., 1996). For example, Krauss and colleagues (2000) suggested that spatial or motoric features expressed in gesture may cross-modally prime the equivalent features in the speaker's semantic representation of a word, making that word more highly activated and consequently more accessible. The proposed activation function is compatible with some versions of the lexical retrieval hypothesis. Specifically, the activation function of gesture may boost activation for spatio-motoric features, which in turn, via a process of spreading activation, could activate words that are strongly associated with those features.

Note that Krauss et al. (2000) proposed that gesture facilitates lexical retrieval when gesture activates spatio-motoric features of the semantic representation of a word. According to this view, a gesture indicating a round shape could not facilitate retrieval of the word *cake* because "Round is not a semantic feature of the word *cake*" (p. 272). In contrast, according to the gesture-for-conceptualization hypothesis, if roundness is strongly associated with the concept of cake, then the gesture should facilitate the retrieval of the word "cake" via spreading activation. Put another way, according to the gesture-for-conceptualization hypothesis, gestural facilitation of lexical retrieval may be a down-stream effect of gesture activating spatio-motoric representations. This perspective provides a potential interpretation for the inconsistent findings in the literature regarding gestural facilitation of lexical retrieval—Frick-Horbury and Guttentag (1998) and Pine, Bird, and Kirk (2007) reported evidence that gesture facilitates lexical retrieval, but Beattie and Coughlan (1999) did not. It may be that in some cases, participants' gestures did not activate spatio-motoric features that were strongly associated with target words in the word retrieval tasks, so they did not facilitate lexical retrieval.

The gesture-for-conceptualization hypothesis also proposes that gesture manipulates spatio-motoric information. This idea stems from our interpretation of evidence that producing gestures facilitates mental rotation performance (Chu & Kita, 2011), mental abacus performance (Hatano et al., 1977), and penetrative thinking (Atit et al., 2015). No existing theories have proposed this function.

The gesture-for-conceptualization hypothesis also proposes that gesture packages spatio-motoric representations for thinking and speaking. This idea builds on the information packaging hypothesis that has been put forward for co-speech gesture, and that has received extensive empirical support (Kita, 2000; Alibali, Kita, & Young, 2000; see Alibali, Yeo, et al., in press, for a review). The current proposal extends this idea to thinking more generally, encompassing findings from both co-speech and co-thought gestures.

The gesture-for-conceptualization hypothesis proposes that gesture explores spatio-motoric information. The idea stems from Kita's (2000) interpretation of speech-gesture mismatches, as a part of the explanation of how gesture searches for information in the context of the information packaging hypothesis. The current proposal further develops this idea, based on new empirical findings.

The four functions posited by the gesture-for-conceptualization hypothesis may also explain evidence that co-speech gesture lightens the cognitive load of speaking (e.g., Goldin-Meadow et al., 2001; Pouw, De Nooijer, Van Gog, Zwaan, & Paas, 2014). The most direct evidence for this idea comes from studies in which speakers explain their solutions to mathematical equations, either with or without gesturing, while maintaining verbal or visual information in working memory (Cook, Yip, & Goldin-Meadow, 2012; Goldin-Meadow et al., 2001; Marstaller & Burianova, 2013). Participants recall the verbal or visual information better when they gesture during the explanation task. It is possible that gesture reduces cognitive load as a down-stream effect of the four functions of gestures identified in the current proposal. That is, the explanation task may have been made easier because gesture activated, manipulated, packaged or explored spatio-motoric information, and consequently more resources were available for the memory task.

We argue that we need exactly these four proposed functions (not more, not fewer) to explain all the relevant findings in the current literature. However, in this regard, we need to consider two, related issues. First, gesture's impact on cognition can be described at different levels of analysis. We have characterized the functions of gesture at a behavioral level; however, other approaches may describe functions at other levels, such as at the neural level (e.g., stimulating neural processes in one of the cerebral hemispheres; Argyriou et al., in press). There may be other levels of analysis, yet to be identified, at which gesture's functions can be described. Second, the four proposed functions can have "down-stream" benefits on other cognitive processes in various ways. For example, consider the well-documented benefits of gesture for learning. It has been proposed that gesture facilitates learning because it lightens cognitive load or changes task representations (Goldin-Meadow & Wagner, 2005). In this vein, gesture may facilitate learning by facilitating the processing of spatio-motoric information relevant to learning. Learning may especially benefit from gesture's exploration function, in light of the flexible and malleable nature of schematic gestural representation. Producing gestures can help learners to discover new conceptualizations of problems and to change their problem representations.

The gesture-for-conceptualization hypothesis holds that the schematic nature of gestural representation shapes the four functions of gestures in specific ways. First, schematization facilitates the generalization of knowledge to new contexts. This role of schematization has been discussed by Novack et al. (2014) and Goldin-Meadow (2015). The other two roles—making processing more efficient and making representations more flexible and open to change—are novel proposals.

Gestures About Spatio-Motoric and Abstract Concepts With Which We Have No Direct Bodily Experience

Gestures often depict physical events with which we have no direct experience, such as movements of molecules (Stieff, 2011) or tectonic plates (Singer, Radinsky, & Goldman, 2008). Does our theory apply to such gestures, despite our claim that gestures are generated from the processes that generate practical actions? We argue that it does. The action generation process can plan gestural movements in the "virtual environment" (p. 165) that are created as imagery, as well as ones in the physical environment (Kita, 2000). When molecules or tectonic plates are imagined as manipulable objects, the gesturing hand may move as if to grasp and move these objects (Singer et al., 2008; Stieff, 2011). We do not see any fundamental differences between such gestures and gestures that move as if to grasp and move real objects; thus, our theory should apply to both types of gestures.

Gestures can also metaphorically express abstract concepts (Cienki & Müller, 2008; McNeill, 1992); for example, the flow of time can be gesturally expressed as movement in space (e.g., Alibali & Nathan, 2012; Kita, Danziger, & Stolz, 2001), the magnitudes of numbers can be gesturally expressed via the relative spatial locations of fingers or hands (e.g., Weinberg, Fukawa-Conolly, & Wiesner, 2015), and having an idea can be gesturally expressed as holding an imaginary object in the hand (e.g., Kita, de Condappa, & Mohr, 2007). We argue that our theory also applies to metaphoric gestures. Because metaphoric gestures depict location, motion and action in schematic ways, just as nonmetaphoric gestures do, it is parsimonious to assume that these two types of gestures are generated by the same mechanism and that they have the same functions.

Many metaphors link abstract concepts to concrete, spatio-motoric concepts that are based on the way our body physically interacts with the environment (Lakoff & Johnson, 1980; Lakoff & Núñez, 2000; Johnson, 1987). Metaphoric gestures regularly express such spatio-motoric source concepts (see Alibali & Nathan, 2012; Núñez & Marghetis, 2014). They can be seen as representational hand movements, acting in the "virtual environment" (Kita, 2000, p. 165), just like the gestures about molecules and tectonic plates mentioned above. Therefore, like nonmetaphoric gestures, metaphoric gestures should affect abstract concepts by activating, manipulating, packaging and exploring their underlying spatio-motoric representations. In fact, as reviewed above, there is evidence that metaphoric gestures activate spatio-motoric representations of abstract concepts (Argyriou & Kita, 2013; Argyriou et al., in press; Beaudoin-Ryan & Goldin-Meadow, 2014). We suggest that our theory applies to both metaphoric and nonmetaphoric gestures, though further empirical studies are needed.

When Do Gestures Hinder or Facilitate?

To make predictions about whether gesture will be helpful or harmful on a given task, relative to not gesturing or relative to action, one must consider the fit between the task goals and the kind of schematic spatio-motoric representations that gesture is adept at activating or generating. To illustrate this point, let us consider cases in which gesture hinders or facilitates problem solving. As discussed above, in gear movement prediction problems, producing gestures inhibits solvers' progression to a more abstract strategy based on whether the number of gears is even or odd (Alibali, Spencer, et al., 2011). Participants were less likely to find this parity-based strategy, which is more efficient, when they were allowed to gesture, as compared to when they were prohibited from gesturing. In contrast, when solving mental rotation problems, producing gestures led to better performance than not producing gestures (Chu & Kita, 2011). We argue that, if strategies based on schematic spatio-motoric representations created by gesture are appropriate or efficient for the task at hand, gesture should facilitate performance; if not, gesture may actually hinder performance.

Relationship Between Co-Speech Gestures and Co-Thought Gestures

One key claim of the gesture-for-conceptualization hypothesis is that both co-speech and co-thought gestures are generated from the same system that generates practical action. This claim is supported by parallel findings for these two types of gestures. First, people produce co-speech gestures more frequently when speaking is more challenging, and they produce co-thought gestures more frequently when problem solving is more challenging (e.g., for co-speech gestures: Kita & Davies, 2009; Melinger & Kita, 2007; Hostetter et al., 2007; Rauscher et al., 1996; Wesp et al., 2001; for co-thought gestures: Chu & Kita, 2011). Second, people produce both co-speech and co-thought gestures more frequently when talking or thinking about stimulus objects that afford action more strongly, compared to talking or thinking about objects that afford action less strongly (Chu & Kita, 2016; Hostetter, 2014; Masson-Carro et al., 2015; Pine et al., 2010). Third, there are parallel changes in co-speech and co-thought gestures over the course of learning to solve problems. In a mental rotation task, the representational content of both types of gestures changed from more object-anchored forms to less object-anchored forms over time, both when people solved the problems while speaking aloud and when they solved them silently (Chu & Kita, 2008). Fourth, suppressing gestures can lead to less frequent use of problem-solving strategies that involve simulating physical movements of objects, and this pattern holds for both co-speech and co-thought gestures (Alibali, Spencer, et al., 2011). Fifth, people who produce co-thought gestures more frequently also produce co-speech gestures more frequently (Chu & Kita, 2016). Taken together, these parallel findings from diverse paradigms and diverse tasks support the claims that both types of gestures originate from the same system and that they function in similar ways.

It should be noted that the co-thought gestures discussed in this article do not include a special type of communicative "silent gestures" that people produce when they are required to describe objects, scenes or events in gesture without speech (e.g., Goldin-Meadow & Brentari, 2016; Goldin-Meadow, So, Özyürek, & Mylander, 2008; Özcaliskan, Lucero, & Goldin-Meadow, 2016). These silent gestures are produced to replace speech and to fulfill communicative functions; the form of these silent gestures is largely shaped by communicative demands. According to Goldin-Meadow and Brentari (2016), these communicative silent gestures often have sign-language-like properties, and they are discrete in form, with each gesture representing a word-like unit. These communicative silent gestures are qualitatively different from the co-thought gestures discussed in this article, which serve primarily self-oriented rather than communicative functions. It remains an open question what self-oriented functions such communicative "silent gestures" may serve.

Relationship Between Self-Oriented and Communicative Functions of Gestures

In this article, we have focused on the self-oriented functions of gesture; however, it is undeniable that gesture, especially co-speech gesture, also plays a role in communication (Hostetter, 2011; Kendon, 1994; Streeck, 2009). We agree with the view in the literature that the self-oriented and communicative functions of gesture are not mutually exclusive (Alibali, Heath, & Myers, 2001; Driskell & Radtke, 2003; Jacobs & Garnham, 2007); indeed, the very same gestures that contribute to activating, manipulating, packaging, and exploring spatio-motoric information may also communicate such information to others.

There are two ways in which people express themselves through gestures: Speakers can "give" or "give off" information (Goffman, 1956) in gestures. In the former case, speakers deliberately encode information in gestures to be received by the recipient. In the latter case, speakers express information in gestures without deliberate communicative intent, but the information is nevertheless taken up by the recipient. In both cases, gestures may serve both communicative and self-oriented functions.

Giving information in gesture is apparent when a speaker strategically chooses to communicate some information via gesture. Speakers may index their gestures verbally (e.g., "it was shaped like this") or they may simply use gestures that convey rich (and relevant) information not expressed in speech. Hostetter and Alibali (2011) suggested that speakers who have spatial skills that outstrip their verbal skills may be especially likely to use gestures in this way, allowing gesture to do much of the work of communicating. Speakers also give information in gesture when they are directed to do so, such as in experimental settings in which an experimenter instructs participants to produce certain gestures (e.g., Novack et al., 2014; Mol & Kita, 2012). Such deliberate gestures influence the gesturers' learning (Novack et al., 2014) and their syntactic packaging of utterances (Mol & Kita, 2012); that is, these gestures serve self-oriented functions in both speaking and thinking.

Giving off information in gesture is apparent in children's spontaneous gesture during their explanations of Piagetian conservation tasks. As in Figure 5, when explaining a judgment in a liquid quantity task, a child might explore the height, width, and cross-sectional area of the container in gestures, but focus only on width and area in his verbal response. The child's teacher might detect the information about height that the child expresses uniquely in gesture—thus, the child's gestural exploration may communicate to the teacher what is "on his mind," even though the child did not produce it with intention to communicate (see Goldin-Meadow, Wein, & Chang, 1992, for evidence that adults do detect information children express uniquely in gesture in conservation tasks). The teacher might even go on to adjust his or her ongoing interaction with the child to take that information into consideration (see Alibali, Flevares, & Goldin-Meadow, 1997). Thus, these gestures clearly "give off" information. At the same time, these gestures serve self-oriented functions. When the availability of gestures is manipulated, children's verbally expressed reasoning is affected (Alibali & Kita, 2010).

To summarize, gestures can simultaneously serve both self-oriented and communicative functions—and this holds, regardless of how strong or explicit the communicative motivation for gesture production is.

Role of Schematization in Communicative Functions of Gesture

We argue that the schematic nature of gestural representation not only shapes the self-oriented functions of gesture, but also influences how the recipient schematizes the situation at hand. That is, speakers' gestures can help their interlocutors to schematize the relevant information from a complex spatial display—and this can occur for spatial displays that are physical or virtual.

One setting in which this regularly occurs is in classrooms, where teachers often use gesture to help students schematize material in appropriate ways. For example, consider a middle-school mathematics teacher providing a lesson about slope and intercept (example drawn from the teacher described in Alibali et al., 2013). In this lesson, the teacher had graphed three equations ($y = 4x$, $y = 2x$, and $y = 2x+15$) all on the same graph; note that two of these lines share the same slope (2), and two share the same intercept (0). At this point in the lesson, the teacher wished to highlight for his students that the *slopes* of two of the lines were the same. He said, "Take a look at these two equations," (referring to the equations represented by the lines) while producing a gesture that schematized the parallelism—that is, the identical slopes—of the two lines (depicted in Figure 9). Note that the teacher could have pointed to the intercepts of the two lines or to some other point along their length, or he could have gestured to the lines in some other way that did not encode their parallelism. But, the key point at this moment in the lesson was the fact that the two lines had the same slopes, and this parallelism was what he chose to schematize in his gesture. Moments later, the teacher said, "They run parallel to each other" while producing a similar gesture in neutral space (facing toward the students), in this case, further schematizing the parallelism of the lines, away from the specific instance depicted on the graph. In our view, teachers' schematizing gestures implement a form of instructional "concreteness fading" (Fyfe, McNeil, Son, & Goldstone, 2014), in the sense that teachers

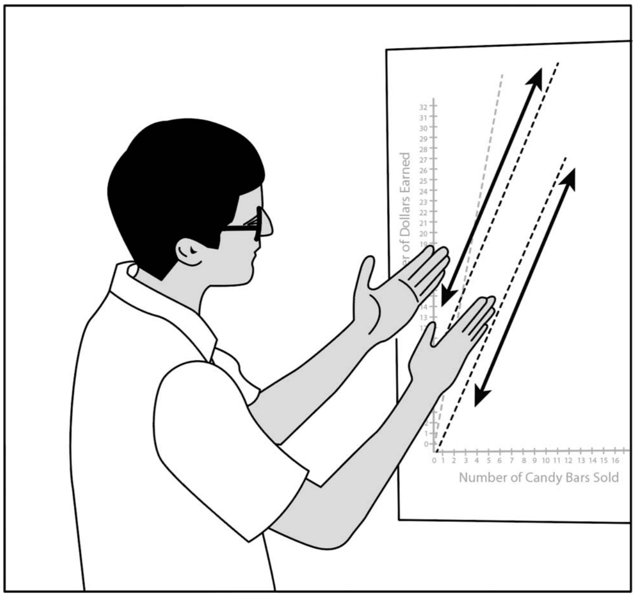

Figure 9. A teacher highlighting that the lines for two equations are parallel, while saying, "Take a look at these two equations." The gesture schematizes a specific aspect of the lines—their identical slopes— that is crucial at this point in the lesson.

use gesture to guide students to focus only on crucial properties of a visual representation (those depicted in gesture) and to ignore extraneous details (in this case, the other line on the graph, the intercepts of the lines, the axes of the graph, and so forth). Thus, we suggest that teachers' gestures schematize for students what is most relevant at that moment in the unfolding discourse of the lesson. Although we do not have data on what the students in this lesson gleaned from the teacher's "parallel" gesture, we argue that, in general, speakers' gestures have the potential to influence, not only their own schematization, but also their listeners' schematization of the topic at hand.

Indeed, research on children's language learning demonstrates that speaker's gestures can affect listeners' schematization of an object or event. Mumford and Kita (2014) investigated this process by having an adult speaker use a novel verb ("Look! She is blicking") as children watched a video scene in which a hand moved objects in a particular way (pushing strips of cloth) into a particular configuration (vertical stripes). The novel verb was ambiguous between two possible referents: acting on objects in a particular manner (pushing) or causing the end state (making vertical stripes). When the adult accompanied the novel verb with a gesture that highlighted the manner of action, children interpreted the verb as characterizing manner; when the adult accompanied the novel verb with a gesture that highlighted the end state, children interpreted the verb as referring to making the end state. Thus, when learning a novel verb while watching a complex scene, children used the speaker's gestures to schematize the scene in their effort to find the referent of the novel verb. The speaker's gesture helped children to schematize the scene by focusing on only one aspect of the scene. Children who saw different gestures (with speech perfectly controlled) schematized the scene in different ways, and this led them to make different inferences about the referent.

We suggest that speakers' gestures play a role in listeners' comprehension that is similar to the role of diagrams and other schematic representations in problem solving. Diagrams schematize and make explicit spatial aspects of problems; highlighting such elements has consequences for how problems are solved (e.g., Bauer & Johnson-Laird, 1993; Butcher, 2006; Kang, Tversky, & Black, 2015). In the same way, speakers' gestures schematize spatio-motoric aspects of the topic at hand, and highlighting such elements has consequences for listeners' understanding.

To summarize, gestures promote specific ways of schematizing in people who see those gestures. We argue that speakers' gestures foster appropriate ways of schematizing complex information in their listeners, and that this is one of the key ways in which gesture contributes to communication.

Conclusion

People spontaneously produce gestures both when they speak and, in some cases, when they think silently. Though gestures, especially co-speech gestures, can play important roles in communication, they are not a mere "output system," which simply externalizes pre-existing mental representations by means of body movements. Instead, we argue that gesture has important self-oriented functions. To explain gesture's self-oriented functions, we have presented the gesture-for-conceptualization hypothesis, which holds that (a) gesture activates, manipulates, packages and explores spatio-motoric information for the purposes of speaking and thinking, and (b) gesture schematizes information, and this schematization process shapes these four functions. These claims are based on the assumption that gesture is a representational use of the general-purpose action generation system, which also generates practical actions. Furthermore, according to the gesture-for-conceptualization hypothesis, gesture's influence is not confined to speaking and reasoning about spatio-motoric information, but also extends to abstract domains via metaphoric gestures. Finally, gesture's influence is not limited to speakers; speakers' schematization of information in gesture influences listeners' thinking, as well. In these ways, gesture plays a central role in human cognition.

References

Alibali, M. W., Flevares, L., & Goldin-Meadow, S. (1997). Assessing knowledge conveyed in gesture: Do teachers have the upper hand? *Journal of Educational Psychology, 89,* 183–193. http://dx.doi.org/10.1037/0022-0663.89.1.183

Alibali, M. W., & Goldin-Meadow, S. (1993). Gesture-speech mismatch and mechanisms of learning: What the hands reveal about a child's state of mind. *Cognitive Psychology, 25,* 468–523. http://dx.doi.org/10.1006/cogp.1993.1012

Alibali, M. W., Heath, D. C., & Myers, H. J. (2001). Effects of visibility between speaker and listener on gesture production: Some gestures are meant to be seen. *Journal of Memory and Language, 44,* 169–188. http://dx.doi.org/10.1006/jmla.2000.2752

Alibali, M. W., & Kita, S. (2010). Gesture highlights perceptually present information for speakers. *Gesture, 10,* 3–28. http://dx.doi.org/10.1075/gest.10.1.02ali

Alibali, M. W., Kita, S., & Young, A. (2000). Gesture and the process of speech production: We think, therefore we gesture. *Language and Cognitive Processes, 15,* 593–613. http://dx.doi.org/10.1080/016909600750040571

Alibali, M. W., & Nathan, M. J. (2012). Embodiment in mathematics teaching and learning: Evidence from learners' and teachers' gestures. *Journal of the Learning Sciences, 21,* 247–286. http://dx.doi.org/10.1080/10508406.2011.611446

Alibali, M. W., Nathan, M. J., & Fujimori, Y. (2011). Gestures in the mathematics classroom: What's the point? In N. Stein & S. Raudenbush (Eds.), *Developmental Cognitive Science Goes To School* (pp. 219–234). New York, NY: Routledge, Taylor and Francis.

Alibali, M. W., Spencer, R. C., Knox, L., & Kita, S. (2011). Spontaneous gestures influence strategy choices in problem solving. *Psychological Science, 22,* 1138–1144. http://dx.doi.org/10.1177/0956797611417722

Alibali, M. W., Yeo, A., Hostetter, A. B., & Kita, S. (in press). Representational gestures help speakers package information for speaking. In R. B. Church, M. W. Alibali, & S. D. Kelly (Eds.), *Why gesture? How the hands function in speaking, thinking and communicating*. Amsterdam, the Netherlands: John Benjamins.

Alibali, M. W., Young, A. G., Crooks, N. M., Yeo, A., Ledesma, I., Nathan, M. J., . . . Knuth, E. J. (2013). Students learn more when their teacher has learned to gesture effectively. *Gesture, 13,* 210–233. http://dx.doi.org/10.1075/gest.13.2.05ali

Annett, J. (1990). Relations between verbal and gestural explanations. In G. E. Hammond (Ed.), *Cerebral control of speech and limb movements* (pp. 327–346). Amsterdam, the Netherlands: Elsevier Science Publishers. http://dx.doi.org/10.1016/S0166-4115(08)60654-8

Argyriou, P., & Kita, S. (2013). The effect of left-hand gestures on metaphor explanation. In M. Knaff, M. Pauen, N. Sebanz, & I. Wachsmuth (Eds.), *Proceedings of the 35th Annual Conference of the Cognitive Science Society* (pp. 1762–1767). Austin, TX: Cognitive Science Society.

Argyriou, P., Mohr, C., & Kita, S. (in press). Hand matters: Left-hand gestures enhance metaphor explanation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*.

Atit, K., Gagnier, K., & Shipley, T. (2015). Student gestures aid penetrative thinking. *Journal of Geoscience Education, 63,* 66–72. http://dx.doi.org/10.5408/14-008.1

Bauer, M. I., & Johnson-Laird, P. N. (1993). How diagrams can improve reasoning. *Psychological Science, 4,* 372–378. http://dx.doi.org/10.1111/j.1467-9280.1993.tb00584.x

Beattie, G., & Coughlan, J. (1999). An experimental investigation of the role of iconic gestures in lexical access using the tip-of-the-tongue phenomenon. *British Journal of Psychology, 90,* 35–56. http://dx.doi.org/10.1348/000712699161251

Beaudoin-Ryan, L., & Goldin-Meadow, S. (2014). Teaching moral reasoning through gesture. *Developmental Science, 17,* 984–990. http://dx.doi.org/10.1111/desc.12180

Beilock, S. L., & Goldin-Meadow, S. (2010). Gesture changes thought by grounding it in action. *Psychological Science, 21,* 1605–1610. http://dx.doi.org/10.1177/0956797610385353

Bock, K., & Cutting, J. C. (1992). Regulating mental energy: Performance units in language production. *Journal of Memory and Language, 31,* 99–127. http://dx.doi.org/10.1016/0749-596X(92)90007-K

Broaders, S. C., Cook, S. W., Mitchell, Z., & Goldin-Meadow, S. (2007). Making children gesture brings out implicit knowledge and leads to learning. *Journal of Experimental Psychology: General, 136,* 539–550. http://dx.doi.org/10.1037/0096-3445.136.4.539

Brooks, N. B., Barner, D., Frank, M., & Goldin-Meadow, S. (2014, July). *The function of gesture in mental abacus computation*. Paper presented at the Annual Meeting of the Cognitive Science Society, Quebec City, Canada.

Butcher, K. R. (2006). Learning from text with diagrams: Promoting mental model development and inference generation. *Journal of Educational Psychology, 98,* 182–197. http://dx.doi.org/10.1037/0022-0663.98.1.182

Butterworth, B., & Hadar, U. (1989). Gesture, speech, and computational stages: A reply to McNeill. *Psychological Review, 96,* 168–174. http://dx.doi.org/10.1037/0033-295X.96.1.168

Casasanto, D., & Dijkstra, K. (2010). Motor action and emotional memory. *Cognition, 115,* 179–185. http://dx.doi.org/10.1016/j.cognition.2009.11.002

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. http://dx.doi.org/10.1037/a0013157

Chu, M., & Kita, S. (2011). The nature of gestures' beneficial role in spatial problem solving. *Journal of Experimental Psychology: General, 140,* 102–116. http://dx.doi.org/10.1037/a0021790

Chu, M., & Kita, S. (2016). Co-thought and co-speech gestures are generated by the same action generation process. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 42,* 257–270.

Church, R. B., & Goldin-Meadow, S. (1986). The mismatch between gesture and speech as an index of transitional knowledge. *Cognition, 23,* 43–71. http://dx.doi.org/10.1016/0010-0277(86)90053-3

Cienki, A., & Müller, C. (Eds.). (2008). *Metaphor and gesture*. Amsterdam, the Netherlands: John Benjamins. http://dx.doi.org/10.1075/gs.3

Clark, H. H. (1996). *Using language*. Cambridge, UK: Cambridge University Press. http://dx.doi.org/10.1017/CBO9780511620539

Clark, H. H. (2003). Pointing and placing. In S. Kita (Ed.), *Pointing: Where language, cognition and culture meet* (pp. 243–268). Hillsdale, NJ: Erlbaum.

Cook, S. W., Mitchell, Z., & Goldin-Meadow, S. (2008). Gesturing makes learning last. *Cognition, 106,* 1047–1058. http://dx.doi.org/10.1016/j.cognition.2007.04.010

Cook, S. W., & Tanenhaus, M. K. (2009). Embodied communication: Speakers' gestures affect listeners' actions. *Cognition, 113,* 98–104. http://dx.doi.org/10.1016/j.cognition.2009.06.006

Cook, S. W., Yip, T. K., & Goldin-Meadow, S. (2012). Gestures, but not meaningless movements, lighten working memory load when explaining math. *Language and Cognitive Processes, 27,* 594–610. http://dx.doi.org/10.1080/01690965.2011.567074

Delgado, B., Gómez, J. C., & Sarriá, E. (2011). Pointing gestures as a cognitive tool in young children: Experimental evidence. *Journal of Experimental Child Psychology, 110,* 299–312. http://dx.doi.org/10.1016/j.jecp.2011.04.010

de Ruiter, J. P. (1998). *Gesture and speech production*. Nijmegen, the Netherlands: Katholieke Universiteit Nijmegen.

de Ruiter, J. P. (2000). The production of gesture and speech. In D. McNeill (Ed.), *Language and gesture* (pp. 284–311). Cambridge, UK: Cambridge University Press. http://dx.doi.org/10.1017/CBO9780511620850.018

Driskell, J. E., & Radtke, P. H. (2003). The effect of gesture on speech production and comprehension. *Human Factors, 45,* 445–454. http://dx.doi.org/10.1518/hfes.45.3.445.27258

Efron, D. (1941). *Gesture, race and culture*. The Hague, the Netherlands: Mouton.

Ehrlich, S. B., Levine, S. C., & Goldin-Meadow, S. (2006). The importance of gesture in children's spatial reasoning. *Developmental Psychology, 42,* 1259–1268. http://dx.doi.org/10.1037/0012-1649.42.6.1259

Ekman, P., & Friesen, W. V. (1969). The repertoire of non-verbal behavior: Categories, origins, usage, and coding. *Semiotica, 1,* 49–98. http://dx.doi.org/10.1515/semi.1969.1.1.49

Feyereisen, P., & Havard, I. (1999). Mental imagery and production of hand gestures while speaking in younger and older adults. *Journal of Nonverbal Behavior, 23,* 153–171. http://dx.doi.org/10.1023/A:1021487510204

Freedman, N. (1977). Hands, words, and mind: On the structuralization of body movements during discourse and the capacity for verbal representation. In N. Freedman & S. Grand (Eds.), *Communicative structures and psychic structures* (pp. 109–132). New York, NY: Plenum Press. http://dx.doi.org/10.1007/978-1-4757-0492-1_6

Frick-Horbury, D., & Guttentag, R. E. (1998). The effects of restricting hand gesture production on lexical retrieval and free recall. *The American Journal of Psychology, 111,* 43–62. http://dx.doi.org/10.2307/1423536

Fyfe, E. R., McNeil, N. M., Son, J. Y., & Goldstone, R. (2014). Concreteness fading in mathematics and science instruction: A systematic review. *Educational Psychology Review, 26,* 9–25. http://dx.doi.org/10.1007/s10648-014-9249-3

Gibson, J. J. (1979). *The ecological approach to visual perception*. Hillsdale, NJ: Erlbaum.

Goffman, E. (1956). *The presentation of self in everyday life*. Edinburgh, Scotland: University of Edinburgh Social Sciences Research Centre.

Goldin-Meadow, S. (2003). *Hearing gesture: How our hands help us think*. Cambridge, MA: Harvard University Press.

Goldin-Meadow, S. (2015). From action to abstraction: Gesture as a mechanism of change. *Developmental Review, 38,* 167–184. http://dx.doi.org/10.1016/j.dr.2015.07.007

Goldin-Meadow, S., Alibali, M. W., & Church, R. B. (1993). Transitions in concept acquisition: Using the hand to read the mind. *Psychological Review, 100,* 279–297. http://dx.doi.org/10.1037/0033-295X.100.2.279

Goldin-Meadow, S., & Beilock, S. L. (2010). Action's influence on thought: The case of gesture. *Perspectives on Psychological Science, 5,* 664–674. http://dx.doi.org/10.1177/1745691610388764

Goldin-Meadow, S., & Brentari, D. (2016). Gesture, sign and language: The coming of age of sign language and gesture studies. *Behavioral and Brain Sciences*. Advance online publication. http://dx.doi.org/10.1017/S0140525X15001247

Goldin-Meadow, S., Cook, S. W., & Mitchell, Z. A. (2009). Gesturing gives children new ideas about math. *Psychological Science, 20,* 267–272. http://dx.doi.org/10.1111/j.1467-9280.2009.02297.x

Goldin-Meadow, S., Nusbaum, H., Kelly, S. D., & Wagner, S. (2001). Explaining math: Gesturing lightens the load. *Psychological Science, 12,* 516–522. http://dx.doi.org/10.1111/1467-9280.00395

Goldin-Meadow, S., So, W. C., Özyürek, A., & Mylander, C. (2008). The natural order of events: How speakers of different languages represent events nonverbally. *Proceedings of the National Academy of Sciences, 105,* 9163–9168. http://dx.doi.org/10.1073/pnas.0710060105

Goldin-Meadow, S., & Wagner, S. M. (2005). How our hands help us learn. *Trends in Cognitive Sciences, 9,* 234–241. http://dx.doi.org/10.1016/j.tics.2005.03.006

Goldin-Meadow, S., Wein, D., & Chang, C. (1992). Assessing knowledge through gesture: Using children's hands to read their minds. *Cognition and Instruction, 9,* 201–219. http://dx.doi.org/10.1207/s1532690xci0903_2

Guilford, J. P. (1967). *The nature of human intelligence*. New York, NY: McGraw-Hill.

Hadar, U., & Butterworth, B. (1997). Iconic gestures, imagery, and word retrieval in speech. *Semiotica, 115,* 147–172.

Hatano, G., Miyake, Y., & Binks, M. G. (1977). Performance of expert abacus operators. *Cognition, 5,* 47–55. http://dx.doi.org/10.1016/0010-0277(77)90016-6

Hegarty, M., Mayer, S., Kriz, S., & Keehner, M. (2005). The role of gestures in mental animation. *Spatial Cognition and Computation, 5,* 33–356. http://dx.doi.org/10.1207/s15427633scc0504_3

Hladký, V., & Havlíček, J. (2013). Was Tinbergen an Aristotelian? Comparison of Tinbergen's four whys and Aristotle's four causes. *Human Ethology Bulletin, 28,* 3–11.

Hostetter, A. B. (2011). When do gestures communicate? A meta-analysis. *Psychological Bulletin, 137,* 297–315. http://dx.doi.org/10.1037/a0022128

Hostetter, A. B. (2014). Action attenuates the effect of visibility on gesture rates. *Cognitive Science, 38,* 1468–1481. http://dx.doi.org/10.1111/cogs.12113

Hostetter, A. B., & Alibali, M. W. (2008). Visible embodiment: Gestures as simulated action. *Psychonomic Bulletin & Review, 15,* 495–514. http://dx.doi.org/10.3758/PBR.15.3.495

Hostetter, A. B., & Alibali, M. W. (2010). Language, gesture, action! A test of the Gesture as Simulated Action framework. *Journal of Memory and Language, 63,* 245–257. http://dx.doi.org/10.1016/j.jml.2010.04.003

Hostetter, A. B., & Alibali, M. W. (2011). Cognitive skills and gesture–speech redundancy: Formulation difficulty or communicative strategy? *Gesture, 11,* 40–60. http://dx.doi.org/10.1075/gest.11.1.03hos

Hostetter, A. B., Alibali, M. W., & Bartholomew, A. (2011). Gesture during mental rotation. In L. Carlson, C. Hoelscher & T. F. Shipley, (Eds.), *Proceedings of the 33rd Annual Conference of the Cognitive Science Society* (pp. 1448–1453). Austin, TX: Cognitive Science Society.

Hostetter, A. B., Alibali, M. W., & Kita, S. (2007). I see it in my hands' eye: Representational gestures reflect conceptual demands. *Language and Cognitive Processes, 22,* 313–336. http://dx.doi.org/10.1080/01690960600632812

Hostetter, A. B., & Boncoddo, R. (in press). Gestures highlight perceptual-motor representations in thinking. In R. B. Church, M. W. Alibali, & S. D. Kelly (Eds.), *Why gesture? How the hands function in speaking, thinking and communicating*. Amsterdam, the Netherlands: John Benjamins.

Jacobs, N., & Garnham, A. (2007). The role of conversational hand gestures in a narrative task. *Journal of Memory and Language, 56,* 291–303. http://dx.doi.org/10.1016/j.jml.2006.07.011

Johnson, M. (1987). *The body in the mind. The bodily basis of meaning, imagination, and reason*. Chicago, IL: The University of Chicago Press.

Kang, S., Tversky, B., & Black, J. B. (2015). Coordinating gesture, word, and diagram: Explanations for experts and novices. *Spatial Cognition and Computation, 15,* 1–26. http://dx.doi.org/10.1080/13875868.2014.958837

Kendon, A. (1994). Do gestures communicate? A review. *Research on Language and Social Interaction, 27,* 175–200. http://dx.doi.org/10.1207/s15327973rlsi2703_2

Kendon, A. (2004). *Gesture: Visible action as utterance*. Cambridge, UK: Cambridge University Press. http://dx.doi.org/10.1017/CBO9780511807572

Kirk, E., & Lewis, C. (2016). Gesture facilitates children's creative thinking. *Psychological Science*. Advance online publication. http://dx.doi.org/10.1177/095679761667918

Kita, S. (2000). How representational gestures help speaking. In D. McNeill (Ed.), *Language and gesture* (pp. 162–185). Cambridge, UK: Cambridge University Press. http://dx.doi.org/10.1017/CBO9780511620850.011

Kita, S. (2014). Production of speech-accompanying gesture. In V. Ferreira, M. Goldrick, & M. Miozzo (Eds.), *Oxford handbook of language production* (pp. 451–459). Oxford, UK: Oxford University Press.

Kita, S., Danziger, E., & Stolz, C. (2001). Cultural specificity of spatial schemas, as manifested in spontaneous gestures. In M. Gattis (Ed.), *Spatial schemas and abstract thought* (pp. 115–146). Cambridge, MA: MIT Press.

Kita, S., & Davies, T. S. (2009). Competing conceptual representations tirgger co-speech representational gestures. *Language and Cognitive Processes, 24,* 761–775. http://dx.doi.org/10.1080/01690960802327971

Kita, S., de Condappa, O., & Mohr, C. (2007). Metaphor explanation attenuates the right-hand preference for depictive co-speech gestures that imitate actions. *Brain and Language, 101,* 185–197. http://dx.doi.org/10.1016/j.bandl.2006.11.006

Kita, S., & Özyürek, A. (2003). What does cross-linguistic variation in semantic coordination of speech and gesture reveal? Evidence for an interface representation of spatial thinking and speaking. *Journal of Memory and Language, 48,* 16–32. http://dx.doi.org/10.1016/S0749-596X(02)00505-3

Kita, S., van Gijn, I., & van der Hulst, H. (1998). Movement phases in signs and co-speech gestures, and their transcription by human coders. In I. Wachsmuth & M. Fröhlich (Eds.), *Gesture and sign language in human-computer interactions. Lecture Notes in Artificial Intelligence* (Vol. 1317, pp. 23–35). Berlin, Germany: Springer-Verlag. http://dx.doi.org/10.1007/BFb0052986

Koedinger, K. R., Alibali, M. W., & Nathan, M. J. (2008). Trade-offs between grounded and abstract representations: Evidence from algebra problem solving. *Cognitive Science, 32,* 366–397. http://dx.doi.org/10.1080/03640210701863933

Krahmer, E. J., & Swerts, M. G. J. (2007). The effects of visual beats on prosodic prominence: Acoustic analyses, auditory perception and visual perception. *Journal of Memory and Language, 57,* 396–414. http://dx.doi.org/10.1016/j.jml.2007.06.005

Krauss, R. M., Chen, Y., & Gottesman, R. (2000). Lexical gestures and lexical access: A process model. In D. McNeill (Ed.), *Language and gesture* (pp. 261–283). Cambridge, UK: Cambridge University Press. http://dx.doi.org/10.1017/CBO9780511620850.017

Lakoff, G., & Johnson, M. (1980). *Metaphors we live by*. Chicago, IL: University of Chicago Press.

Lakoff, & R. Núñez. (2000). *Where mathematics comes from: How the embodied mind brings mathematics into being*. New York, NY: Basic Books.

LeBaron, C. D., & Streeck, J. (2000). Gesture, knowledge, and the world. In D. McNeill (Ed.), *Gesture and language* (pp. 118–138). Chicago, IL: University of Chicago Press. http://dx.doi.org/10.1017/CBO9780511620850.008

Levelt, W. (1989). *Speaking: From intention to articulation*. Cambridge, MA: MIT Press.

Marstaller, L., & Burianová, H. (2013). Individual differences in the gesture effect on working memory. *Psychonomic Bulletin & Review, 20,* 496–500. http://dx.doi.org/10.3758/s13423-012-0365-0

Masson-Carro, I., Goudbeek, M., & Krahmer, E. (2016). Can you handle this? The impact of object affordances on how co-speech gestures are produced. *Language, Cognition and Neuroscience, 31,* 430–440. http://dx.doi.org/10.1080/23273798.2015.1108448

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

McNeill, D. (2005). *Gesture and thought*. Chicago, IL: University of Chicago Press. http://dx.doi.org/10.7208/chicago/9780226514642.001.0001

Melinger, A., & Kita, S. (2007). Conceptualisation load triggers gesture production. *Language and Cognitive Processes, 22,* 473–500. http://dx.doi.org/10.1080/01690960600696916

Mol, L., & Kita, S. (2012). Gesture structure affects syntactic structure in speech. In N. Miyake, D. Peebles, & R. P. Cooper (Eds.), *Proceedings of the 34th Annual Conference of the Cognitive Science Society* (pp. 761–766). Austin, TX: Cognitive Science Society.

Morsella, E., & Krauss, R. M. (2004). The role of gestures in spatial working memory and speech. *The American Journal of Psychology, 117,* 411–424. http://dx.doi.org/10.2307/4149008

Müller, C. (1998). *Redebegleitende Gesten: Kulturgeschichte - Theorie - Sprachvergleich*. Berlin, Germany: Berlin Verlag.

Mumford, K. H., & Kita, S. (2014). Children use gesture to interpret novel verb meanings. *Child Development, 85,* 1181–1189. http://dx.doi.org/10.1111/cdev.12188

Newell, A., & Simon, H. A. (1972). *Human problem solving*. Englewood Cliffs, NJ: Prentice Hall.

Novack, M. A., Congdon, E. L., Hemani-Lopez, N., & Goldin-Meadow, S. (2014). From action to abstraction: Using the hands to learn math. *Psychological Science, 25,* 903–910. http://dx.doi.org/10.1177/0956797613518351

Novack, M. A., & Goldin-Meadow, S. (2016). Gesture as representational action: A paper about function. *Psychonomic Bulletin & Review*. Advance online publication. http://dx.doi.org/10.3758/s13423-016-1145-z

Novack, M. A., Wakefield, E. M., & Goldin-Meadow, S. (2016). What makes a movement a gesture? *Cognition, 146,* 339–348. http://dx.doi.org/10.1016/j.cognition.2015.10.014

Núñez, R., & Marghetis, T. (2014). Cognitive linguistics and the concept(s) of number. In R. Cohen Kadosh & A. Dowker (Eds.), *The Oxford handbook of numerical cognition* (pp. 377–400). Oxford, UK: Oxford University Press. http://dx.doi.org/10.1093/oxfordhb/9780199642342.013.023

Özçalışkan, Ş., Lucero, C., & Goldin-Meadow, S. (2016). Does language shape silent gesture? *Cognition, 148,* 10–18. http://dx.doi.org/10.1016/j.cognition.2015.12.001

Perry, M., Church, R. B., & Goldin-Meadow, S. (1988). Transitional knowledge in the acquisition of concepts. *Cognitive Development, 3,* 359–400. http://dx.doi.org/10.1016/0885-2014(88)90021-4

Pine, K. J., Bird, H., & Kirk, E. (2007). The effects of prohibiting gestures on children's lexical retrieval ability. *Developmental Science, 10,* 747–754. http://dx.doi.org/10.1111/j.1467-7687.2007.00610.x

Pine, K. J., Gurney, D. J., & Fletcher, B. (2010). The semantic specificity hypothesis: When gestures do not depend upon the presence of a listener. *Journal of Nonverbal Behavior, 34,* 169–178. http://dx.doi.org/10.1007/s10919-010-0089-7

Pine, K. J., Lufkin, N., & Messer, D. (2004). More gestures than answers: Children learning about balance. *Developmental Psychology, 40,* 1059–1067. http://dx.doi.org/10.1037/0012-1649.40.6.1059

Pouw, W. T. J. L., de Nooijer, J. A., van Gog, T., Zwaan, R. A., & Paas, F. (2014). Toward a more embedded/extended perspective on the cognitive function of gestures. *Frontiers in Psychology, 5,* 359. http://dx.doi.org/10.3389/fpsyg.2014.00359

Rauscher, F. H., Krauss, R. M., & Chen, Y. (1996). Gesture, speech, and lexical access: The role of lexical movements in speech production. *Psychological Science, 7,* 226–231. http://dx.doi.org/10.1111/j.1467-9280.1996.tb00364.x

Rimè, B., Shiaratura, L., Hupet, M., & Ghysselinckx, A. (1984). Effects of relative immobilization on the speaker's nonverbal behavior and on the dialogue imagery level. *Motivation and Emotion, 8,* 311–325. http://dx.doi.org/10.1007/BF00991870

Schwartz, D. L., & Black, J. B. (1996). Shuttling between depictive models and abstract rules: Induction and fallback. *Cognitive Science, 20,* 457–497. http://dx.doi.org/10.1207/s15516709cog2004_1

Sekine, K., Wood, C., & Kita, S. (2016). *Gestural depiction of motion events in narrative increases symbolic distance with age*. Manuscript under review.

Shapiro, L. (2014). *Routledge handbook of embodied cognition*. New York, NY: Routledge.

Singer, M. A., Radinsky, J., & Goldman, S. R. (2008). The role of gesture in meaning construction. *Discourse Processes, 45,* 365–386. http://dx.doi.org/10.1080/01638530802145601

So, W. C., Ching, T. H-W., Lim, P. E., Cheng, X., & Ip, K. Y. (2014). Producing gestures facilitates route learning. *PLoS ONE, 9*(11), e112543. http://dx.doi.org/10.1371/journal.pone.0112543

Spencer, R. C. (2003). *The role of spontaneous gesture in determining problem solving strategies* (Unpublished bachelor's thesis). University of Wisconsin-Madison, Madison, WI.

Stieff, M. (2011). When is a molecule three dimensional? A task-specific role for imagistic reasoning in advanced chemistry. *Science Education, 95,* 310–336. http://dx.doi.org/10.1002/sce.20427

Streeck, J. (1996). How to do things with things: Objets trouvés and symbolization. *Human Studies, 19,* 365–384. http://dx.doi.org/10.1007/BF00188849

Streeck, J. (2009). *Gesturecraft: The manu-facture of meaning*. Amsterdam, the Netherlands: John Benjamins. http://dx.doi.org/10.1075/gs.2

Wagner, S. M., Nusbaum, H., & Goldin-Meadow, S. (2004). Probing the mental representation of gesture: Is handwaving spatial? *Journal of Memory and Language, 50,* 395–407. http://dx.doi.org/10.1016/j.jml.2004.01.002

Weinberg, A., Fukawa-Conolly, T., & Wiesner, E. (2015). Characterizing instructor gestures in a lecture in a proof-based mathematics class. *Educational Studies in Mathematics, 90,* 233–258. http://dx.doi.org/10.1007/s10649-015-9623-1

Wesp, R., Hesse, J., Keutmann, D., & Wheaton, K. (2001). Gestures maintain spatial imagery. *The American Journal of Psychology, 114,* 591–600. http://dx.doi.org/10.2307/1423612

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review, 9,* 625–636. http://dx.doi.org/10.3758/BF03196322

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