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Embodied Cognition in Learning and Teaching

Action, Observation, and Imagination

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A central claim of theories of embodied cognition is that cognitive processes are rooted in the actions of the human body in the physical world. In any given environment and setting, a specific individual has a set of potential perceptual experiences and actions. These experiences and actions depend on the specifics of the individual's body shape, morphology, and scale; the body's sensory and perceptual systems; the neural systems involved in planning and producing actions; and the affordances of these sensory, perceptual, and motor systems in that specific environment and setting. Although there is to date no single, unified theory of embodied cognition, the grounding of thought in perception and action is a common theme across a range of theoretical perspectives (Barsalou, 2008; Glenberg, 1997; Shapiro, 2011; Wilson, 2002).

The view that cognition is grounded in action implies that, across domains of reasoning, fundamental concepts and activities are based in actions of the body. This is the case, even for non-physical, non-observable ideas, which are conceptualized through their relations with sensorimotor experiences via metaphor (Lakoff & Johnson, 1999). From this perspective, then, action should matter for learning, and in turn, for instruction. In this chapter, we consider both learning and teaching from the perspective of embodied cognition, with a special focus on the importance of action.

Points of Contact with Cognitivist and Situated-Cognition Views

An embodied perspective on learning contrasts with more traditional, cognitivist perspectives on learning, which draw on the metaphor of the human brain as an information processing system (DeVega, Glenberg, & Graesser, 2008). As such, cognitivist approaches tend to focus on how arbitrary symbol systems and internal, mental representations mediate behavior. Studies in the cognitivist tradition often examine behavior in tasks and settings that are distant from authentic practices and contexts.

The embodied perspective has more in common with the situated cognition perspective and its assumption that thinking is bound to activities that occur in physical, social, and cultural contexts. From a situated cognition perspective (Robbins & Aydede, 2009), cognition is distributed across (or embedded in) cultural tools, inscriptions, and spaces, as exemplified by cognitive "offloading" to the environment (Wilson, 2002), and extended in the sense that sociocultural and physical settings are viewed as part of the cognitive system (Clark & Chalmers, 1998). The embodied perspective, in contrast, takes as central the physical body, the motor system, and the systems involved in sensing and perceiving. As such, the embodied cognition perspective construes cognition as the goal-directed activity of a human with a particular body in a particular physical environment and setting.

Overview of the Chapter

In this chapter, our focus is on the implications of an embodied cognition perspective for learning and instruction. We focus on three major principles. First, action matters for cognitive performance and learning. Appropriate actions can promote performance and learning, and unaligned actions can interfere. Second, observing others' actions can influence cognitive performance and learning, in the same ways that producing actions does. Third, imagining or simulating actions can also influence cognitive performance and learning. We consider both imagined actions and gestures, which are a form of representational action that manifests simulated actions. Taken together, evidence for these principles converges to highlight the importance of actions—both real and imagined—in cognitive performance, learning, and instruction. A focus on action also has far-reaching implications for central topics in the learning sciences, including instructional design, assessment, and educational technology; we consider these issues in the final section of the chapter.

Our focus on action, observation, and imagination can be illustrated by the forms of behavior that a child produces during a mathematics lesson about numerical equality that uses a pan balance (see Figure 8.1). The child may reason about equality via *action*, as she places cubes in the pans of the pan balance (Panel A); via *observation*, as she looks on while another child places cubes in the pans (Panel B); or via *imagination*, as she thinks about placing the cubes in the pans (Panel C).

Action Matters for Cognition and Learning

The idea that action matters for cognition and learning is rooted in developmental psychological theories, most notably those of Piaget and his successors, and in phenomenology. Both of these theoretical perspectives highlight the sensorimotor origins of knowledge and thought. According to Piaget, action is the foundation of thought; physical operations are internalized and transformed into mental operations, and eventually mental representations (Beilin & Fireman, 2000). Phenomenologists reject this last step and, instead, consider how actions and ways of engaging with the world provide a more direct account of cognition (Dreyfus, 2002). The feasibility of this approach has been demonstrated using mobile robot designs without mental representations (Brooks, 1991).

If cognitive processes are grounded in action, then the nature of the actions that people produce should make a difference for their cognitive performance and learning. Indeed, a growing body of research on language comprehension, problem solving, and mathematical reasoning supports this view. This body of work has revealed that actions that are structurally aligned with key features of the target material can foster comprehension, memory, and learning. In contrast, unaligned actions can interfere with comprehension, memory, and learning.

Language Comprehension

One formulation of the view that language comprehension is grounded in action understanding is that people index words and grammatical structures to real-world experiences (Glenberg & Robertson, 1999). Therefore, comprehending language evokes motor and perceptual affordances. If this is the case, then concurrent motor activity should affect language comprehension—and, indeed, it does. In one compelling demonstration of this effect, participants were asked to read sentences that implied motion away from the body (such as "Close the drawer") or motion towards the body (such as "Open the drawer"). Participants were asked to verify whether the sentences were sensible, either by making arm movements away from their bodies (to press a button farther from the body than the hand-at-rest position) or by making arm movements towards their bodies (to press a button closer to the body than the hand-at-rest position). Participants responded faster when the motion implied in the sentence was aligned with the direction of motion in the response (Glenberg & Kaschak, 2002). Importantly, this phenomenon held, not only for sentences describing concrete, physical

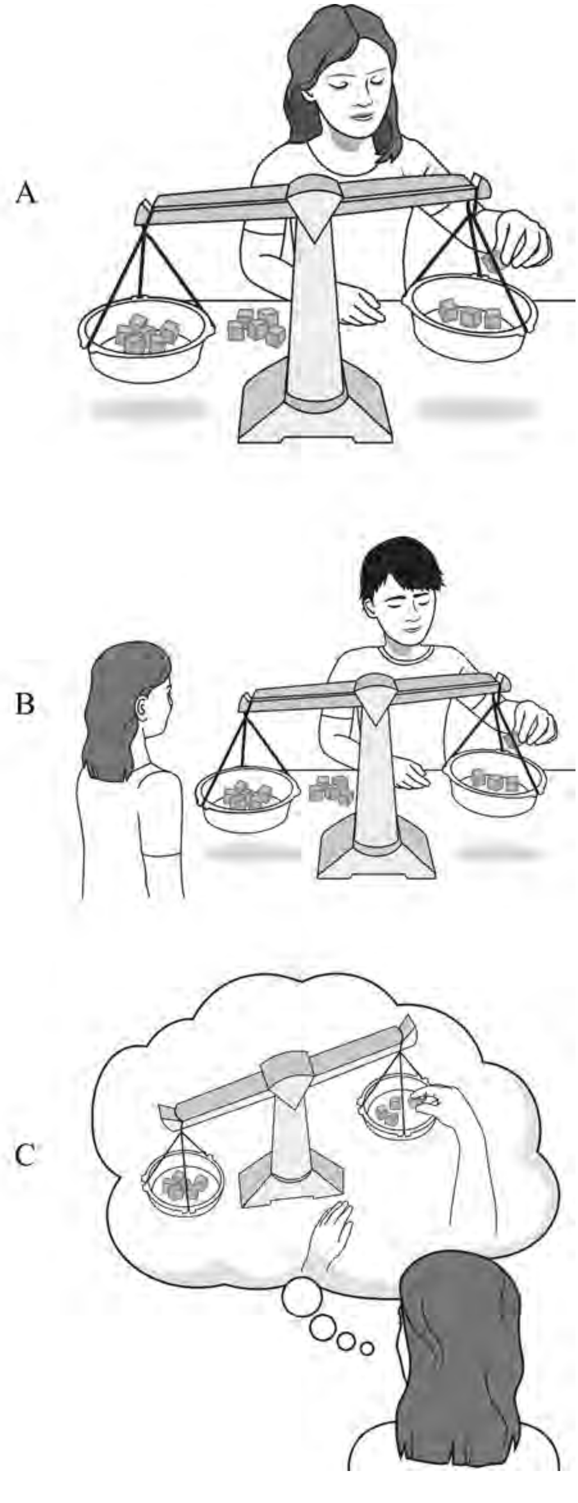

Figure 8.1 A Child Reasoning About Numerical Equality by Producing Actions (Panel A); by Observing Another Child's Actions (Panel B); or by Imagining Actions (Panel C).

Source: Figures available at http://osf.io/ydmrh under a CC-BY4.0 license (Alibali, 2017).

movements, but also for sentences describing the metaphorical movement of abstract entities (such as "Liz told you the story"). Later studies revealed that there is modulation of activity in the hand muscles when comprehending sentences that describe concrete actions and figurative "actions" that involve transfer of information (Glenberg et al., 2008).

Are the same processes involved in more complex contexts of language comprehension and use—for example, in tasks that require more than comprehending simple sentences? Glenberg and colleagues addressed this question in a set of studies on learning from text (Glenberg, Gutierrez, Levin, Japuntich, & Kaschak, 2004). First- and second-grade students were presented with three toy scenarios (a farm, a house, and a gas station) and asked to read brief texts about them. In one condition, children were asked to manipulate the toys (characters and objects, e.g., for the farm scenario, a tractor, a barn, animals, etc.) to correspond to each of the sentences in the text; in another condition, children observed but did not manipulate the toys. Children in the manipulate group showed better memory for the text than children in the observe group, and they were also better at drawing inferences based on the text. Similar findings were obtained when comparable manipulation interventions were implemented for solving mathematical story problems (Glenberg, Jaworski, Rischal, & Levin, 2007) and in small-group settings for reading (Glenberg, Brown, & Levin, 2007). Thus, manipulating relevant objects in text-relevant ways facilitates children's text comprehension, at least for simple passages about concrete objects and situations.

Problem Solving

Action also plays a powerful role in shaping the cognitive processes involved in problem solving. For example, Thomas and Lleras (2007) asked participants to solve a well-known insight problem that had a spatial solution (Duncker's radiation problem). During the solution period, in the guise of an unrelated visual tracking task, participants' eye movements were guided, either in a pattern that aligned with the problem's solution or in a pattern that did not align with the solution. Participants who moved their eyes in a way that aligned with the solution were more likely to solve the insight problem. Importantly, most participants did not suspect that there was a relationship between the tracking task and the insight problem, suggesting that the connection from the eye movements to the spatial solution to the problem was implicit.

Directed actions can also influence problem solving in more academic tasks, such as generating mathematical proofs. Nathan and colleagues (2014) asked undergraduate students to generate proofs for two mathematical statements, after performing either actions that were aligned with the key insights that underlay the proofs or actions that were not aligned with those key insights. Participants who produced aligned actions were more likely to discover those key insights as they worked to generate proofs.

Taken together, these studies help build a case that actions are integral in cognition and learning across a range of tasks, including language comprehension, problem solving, and mathematical reasoning. This view has motivated instructional approaches that involve actions, such as lessons with concrete manipulatives (see Figure 8.1). Indeed, a recent meta-analysis revealed beneficial effects of manipulatives on mathematics learning across a wide range of ages and concepts, although many additional factors moderate these effects (Carbonneau, Marley, & Selig, 2013). In this regard, it is important to consider whether learners must actually *produce* those actions, or whether viewing another's actions or even simply imagining actions might matter, as well. Research suggests that all three—acting, observing, and imagining—influence cognition and learning.

Observing Others' Actions Can Activate Learners' Embodied Knowledge

A large body of research, going back to early social learning theory (e.g., Bandura, 1965), and continuing to the present day (e.g., Chi, Roy & Hausmann, 2008; also see also Rummel & van Gog, this volume) demonstrates that people learn from observing others. Researchers from different theoretical perspectives refer to this process with different terms (e.g., imitative learning, vicarious learning, observational learning) and have offered different views regarding underlying mechanisms. An embodied perspective on this literature highlights the possibility that others' actions may also activate learners' action-based knowledge, and therefore influence their cognition and learning.

Many studies have shown that observing actions activates the same brain regions that are involved in actually executing those actions. Nearly two decades ago, Rizzolatti and colleagues demonstrated that the human motor cortex is activated in similar ways when humans execute motor tasks and when they observe them (Hari et al., 1998; Rizzolatti, Fogassi, & Gallese, 2001). They showed that patterns of brain activation were similar when people manipulated a small object with their hands and when they viewed another person performing that same action. Later research demonstrated the specificity of this effect, showing that viewing actions produced with specific effectors (e.g., the mouth, the hands, or the feet) elicited activation in the corresponding motor areas in people who observed the actions (Buccino et al., 2001). These findings suggest that when people observe an action, they generate an internal simulation of that action in their premotor cortex.

These findings open the possibility that learners need not physically produce actions themselves in order for action to affect their cognition and learning. Viewing others' actions in learning contexts may be sufficient to activate learners' action-based knowledge, or to facilitate learners' generating action-based knowledge.

The claim that individual learning may depend on *others'* actions highlights the importance of considering the learning context as a system involving multiple participants in interaction. The actions produced by a learner's teachers or peers in the learning context have the potential to influence that learner's thinking by activating action-based knowledge. Although many perspectives on learning—including sociocultural and ecological perspectives—highlight the importance of social interactions in learning, an embodied perspective foregrounds others' observed actions as a crucial element of the learning context.

Imagined or Simulated Actions Can Influence Cognition and Learning

Some scholars have highlighted the close ties between imagination and action. Indeed, Nemirovsky and Ferrara (2008) define *imagining* as "entertaining possibilities for action; entertaining (in the sense of 'holding' or 'keeping') a state of readiness for the enactment of possible actions" (p. 159). In our view, imagining involves mentally experiencing actions by engaging in motor imagery or mental simulation of action. This mental experience of action could be triggered in a range of ways, such as by reading or listening to words that describe actions, by planning an intended action, by thinking about performing an action, or by thinking about viewing another person's action.

There is evidence that listening to or reading sentences about actions activates the brain areas involved in producing those actions, suggesting that thinking about actions also engages simulations of actions. In one study (Tettamanti et al., 2005), participants passively listened to sentences involving actions with different effectors ("I bite an apple," "I grasp a knife," "I kick the ball"). The sentences about actions elicited activation in the brain areas involved in action execution and action observation, whereas control sentences about abstract content did not. Moreover, there were additional, specific loci of activation that reflected motor representations of the specific actions (i.e., mouth vs. hand vs. leg actions), suggesting that hearing action-related words led to activation in the corresponding motor regions. In a related study, passively reading the words *lick, pick*, and *kick* activated the same brain regions that were activated when participants moved their tongues, fingers, and feet (Hauk, Johnsrude, & Pulvermüller, 2004). Further, words denoting more specific actions (e.g., *wipe*) elicited greater activation in motor areas than words denoting more general actions (e.g., *clean*) (van Dam, Rueschemeyer, & Bekkering, 2010). Taken together, these studies suggest that hearing or reading action words automatically activates the brain regions involved in actually producing those actions.

Indeed, there is evidence suggesting that these forms of "mentally" acting are sufficient for action to influence cognition. In their study of actions and reading comprehension, Glenberg and colleagues (2004) also tested the effect of imagining actions. In one experiment, children practiced imagining rather than actually acting out actions on the task objects described in the text passages. Children who imagined manipulating the objects showed better memory for the text and better inference making than children in a control condition, who read the text twice. Presumably, children who were directed to specifically imagine acting on objects produced richer action simulations that children who simply read the text. Glenberg and colleagues argued that imagining actions conferred benefits for cognition and inference making that were similar to actually performing the actions.

Research in sports psychology has also addressed the relations between imagined action and actual action. Past research in this area focused on whether "mental practice" can influence performance and learning of motor skills. An early meta-analysis demonstrated that imagined actions can indeed influence later performance and learning (Feltz & Landers, 1983). The boundary conditions for such effects remain to be ascertained; however, at a minimum, they highlight the functional similarity—and, in some cases, functional equivalence—of action and action simulations (Beilock & Gonso, 2008).

Simulating action functions like producing action in many key respects, including activating relevant neural circuitry. From this perspective, then, it makes sense that imagining action—either in response to observing another's action or on one's own volition—may affect performance and learning in the same ways that producing action does. In some cases, simulating action may lead to actually producing action: simulations activate premotor and motor areas in the brain, and this activation may give rise to overt action. For example, one could think about tracing the shape of a triangle in the air, and this simulated action might give rise to actual movements that trace a triangle in the air.

Gesture as Simulated Action

The *Gesture as Simulated Action* framework (Hostetter & Alibali, 2008) holds that simulated actions and perceptual states are sometimes manifested in overt behavior as spontaneous gestures, which are a form of action that *represents* actual actions and perceptual states. According to this framework, when the level of activation of an individual's simulation exceeds that individual's "gesture threshold" (which depends on a set of individual, social, and situational factors), that simulation will give rise to a gesture. Gestures typically occur with speech, presumably because producing oral movements for speaking increases overall activation in motor and premotor areas, and this increased activation makes it more likely that activation will exceed the individual's gesture threshold. However, gestures can also occur in the absence of speech. For example, people often gesture without speech when engaging in challenging spatial tasks, such as mentally rotating objects (e.g., Chu & Kita, 2011).

Producing gestures may also feed back to increase the activation level of the simulated actions or perceptual states that gave rise to the gestures. Thus, producing gestures may increase activation on a simulation, and may consequently make an individual more likely to reason with that simulation. For example, in gear movement problems, which involve predicting how one gear will turn if another gear is moved in a particular direction, individuals who produce gestures are more likely to use strategies that involve simulating the movements of each gear (Alibali, Spencer, Knox, & Kita, 2011).

Just as viewing actions has much in common with producing actions, we argue that viewing gestures has much in common with producing gestures—and with producing the actions or experiencing the perceptual states that are represented in those gestures. Thus, viewing others' gestures may evoke simulations of actions in the viewers (Ping, Goldin-Meadow, & Beilock, 2014), and these simulated actions may in turn influence the viewers' thinking and their actions (Cook & Tanenhaus, 2009). Indeed, this may be one of the reasons why teachers' gestures are so influential in affecting student learning (e.g., Cook, Duffy, & Fenn, 2013; Singer & Goldin-Meadow, 2005). Teachers' gestures may evoke simulated actions in their students' thinking, and these simulated actions may in turn give rise to gestures or actions on the part of the students. In fact, students gesture more when their teachers gesture more (Cook & Goldin-Meadow, 2006), lending support to this idea.

This pathway provides a potential mechanism by which demonstrations and instructional gestures may influence learning. In brief, gestures may both manifest simulated actions on the part of the gesture producers (Alibali & Nathan, 2012) and evoke simulated actions on the part of those who observe the gestures (Kita, Alibali, & Chu, 2017).

Implications for Key Topics in the Learning Sciences

Taken together, the lines of work reviewed in this chapter converge to demonstrate the importance of actions—actual, observed, and imagined—in cognition, learning, and instruction. These ideas have implications for several key topics in the learning sciences, including instructional design, assessment, and educational technology.

Instructional Design

An embodied perspective on instructional design highlights the importance of considering students' opportunities to engage in actions, with a focus on "action-concept congruencies" (Lindgren & Johnson-Glenberg, 2013). One strand of research in this vein has focused on designing instructional interventions in which students engage in bodily actions (e.g., Fischer, Moeller, Bientzle, Cress, & Nuerk, 2010; Johnson-Glenberg, Birchfield, Tolentino, & Koziupa, 2013; Nathan & Walkington, 2017) or produce specific gestures (Goldin-Meadow, Cook, & Mitchell, 2009). Another strand of research has focused on concrete manipulatives and the actions they afford (e.g., Martin & Schwartz, 2005; Pouw, van Gog, & Paas, 2014). An emerging approach extends this perspective to digital manipulatives, as touch screen technology also affords actions (Ottmar & Landy, 2017).

An embodied perspective also highlights the potential value of observing others' actions and gestures. A growing body of recent work has sought to characterize the ways in which teachers use gestures in instructional settings and to investigate how teachers' gestures are involved in students' learning (e.g., Alibali et al., 2013; Furuyama, 2000; Richland, 2015). This body of work highlights the role of teachers' gesture in guiding students' simulations of relevant actions and perceptual states (Kang & Tversky, 2016).

Assessment

An embodied perspective on learning also has implications for the assessment of students' knowledge. In this regard, we consider two related issues. First, some action-based knowledge may not be verbally coded. Such knowledge may be readily exhibited in demonstrations or gestures, but it may not be spontaneously expressed in speech or writing. Indeed, many studies have shown that learners often express some aspects of their knowledge uniquely in gestures. Such "mismatching" gestures have been observed across a range of tasks, including conservation of quantity (Church & Goldin-Meadow, 1986), mathematical equations (Perry, Church, & Goldin-Meadow, 1988), and reasoning about balance (Pine, Lufkin, & Messer, 2004), and it has been argued that such gestures reveal the contents of learners' Zones of Proximal Development (Goldin-Meadow, Alibali, & Church, 1993). Given that learners' gestures often reveal information they do not express in speech, it follows that some aspects of learners' knowledge may be inappropriately discounted by assessment methods that consider only knowledge conveyed through speech or writing. Students' actions and gestures can reveal aspects of their knowledge that must be considered if formative assessments are to be accurate. Attending to students' actions and gesture may improve the validity of summative assessments, as well.

Second, assessment practices that prevent learners from producing task-relevant actions and gestures (such as assessment practices that require typing) may actually impair higher-order thinking, such as inference making (Nathan & Martinez, 2015). When assessment practices interfere with the processes involved in embodied thinking, this may compromise the validity of those assessment practices, yielding a false portrayal of what a test taker actually knows. For assessment to be accurate and valid, it may be necessary to use methods that allow learners to engage their bodies.

Educational Technology

As Lee (2015) notes, technological advances support the embodiment of concepts in new ways. The increasing availability of motion capture technologies such as the Kinect™ have made it possible—and practical—to design and implement interventions that elicit, track, and respond to learners' movements. There is an emerging class of embodied learning technologies that expressly uses players' movements to foster learning. Some of the systems in this early wave of embodied designs enlist participants to engage in movements that elicit intended associations and conceptualizations. For example, the GRASP project draws on the gestures and actions that students exhibited during successful reasoning about science phenomena, including gas pressure, heat transfer, and seasons (Lindgren, Wallon, Brown, Mathayas, & Kimball, 2016). Other students can be cued to use such gestures to interact with computer simulations of these phenomena when reasoning about causal mechanisms (Wallon & Lindgren, 2017). As a second example, players of *The Hidden Village* (Nathan & Walkington, 2017) match the actions of in-game agents. These actions are intended to foster players' insights about generalized properties of shapes and space, and these insights in turn may influence their geometry justifications and proofs. The target directed actions were curated from analyses of successful mathematical reasoning.

Embodied learning technologies can also support bottom-up processes that facilitate the generation and exploration of concepts. For example, in the Mathematical Imagery Trainer (Abrahamson & Trninic, 2014), students find the proper pacing of their two hands to represent target proportions (such as 1:2) without overt direction to do so, thereby generating sensorimotor schemes that may foster their conceptual development.

Conclusions

An embodied perspective on learning and instruction highlights the importance of producing, observing, and imagining actions. Actions that are well aligned with target ideas can promote cognitive performance and learning, whereas actions that are not well aligned can interfere. It is not always necessary for learners to produce actions on their own; observing others' actions can also activate action-based knowledge. Imagined or simulated actions can do so, as well, and these simulations may be manifested in gestures, which are a form of representational action. Finally, observing others' actions and gestures may provoke learners to simulate or to produce actions. In these ways, perceiving others' actions and gestures can also influence cognitive performance and learning.

A focus on action requires attention, not only to processes taking place in the learner's own brain and cognitive system, but also to the learner's activities with physical and cultural tools, and to the learner's interactions with other people. The physical and cultural tools that are available to learners both afford and constrain the actions that learners engage in. Learners' interactions with others—for example, in classrooms or in collaborative learning environments—typically involve opportunities for joint action and for observing others' actions. Thus, an embodied perspective on learning and instruction requires a broader view of the learner in physical, cultural, and social context.

In sum, embodied action is a foundational element of learning. As such, embodied action must be viewed as a fundamental construct in the learning sciences, with implications that broadly encompass theories, designs, and practices for assessment, teaching, and learning.

Further Readings

Glenberg, A. M., Gutierrez, T., Levin, J. R., Japuntich, S., & Kaschak, M. P. (2004). Activity and imagined activity can enhance young children's reading comprehension. *Journal of Educational Psychology, 96*(3), 424–436.

A set of empirical studies documenting the implications of action and imagined action in text comprehension and inference making.

Goldin-Meadow, S. (2005). *Hearing gesture: How our hands help us think*. Cambridge, MA: Harvard University Press.

A comprehensive introduction to gesture in reasoning, learning, and teaching.

Hall, R., & Nemirovsky, R. (Eds.). (2012). Modalities of body engagement in mathematical activity and learning [Special Issue]. *Journal of the Learning Sciences, 21*(2).

A compendium of papers representing a range of embodied perspectives on student performance, learning, and teaching of mathematics.

Lakoff, G., & Johnson, M. (1999). *Philosophy in the flesh: The embodied mind and its challenge to Western thought*. New York: Basic Books.

A seminal text that makes a strong case for embodied cognition on philosophical and linguistic grounds.

Shapiro, L. (2011). *Embodied cognition*. New York: Routledge.

An excellent introduction to basic themes and debates regarding embodied cognition.

References

Abrahamson, D., & Trninic, D. (2014). Bringing forth mathematical concepts: Signifying sensorimotor enactment in fields of promoted action. *ZDM*, *47*, 295–306. doi:10.1007/s11858-014-0620-0

Alibali, M. W. (2017, February 27). *Action-observation-imagination figures*. Retrieved from http://osf.io/ydmrh

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

Alibali, M. W., Nathan, M. J., Wolfgram, M. S., Church, R. B., Jacobs, S. A., Martinez, C. J., & Knuth, E. J. (2013). How teachers link ideas in mathematics instruction using speech and gesture: A corpus analysis. *Cognition & Instruction*, *32*, 65–100. doi:10.1080/07370008.2013.858161

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

Bandura, A. (1965). Vicarious processes: A case of no-trial learning. In L. Berkowitz (Ed.), *Advances in experimental social psychology* (Vol. *2*, pp. 1–55). New York: Academic Press.

Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology*, *59*, 617–645. doi:10.1146/annurev.psych.59.103006.093639

Beilin, H., & Fireman, G. (2000). The foundation of Piaget's theories: Physical and mental action. *Advances in Child Development and Behavior*, *27*, 221–246. doi:10.1016/S0065-2407(08)60140-8

Beilock, S. L., & Gonso, S. (2008). Putting in the mind versus putting on the green: Expertise, performance time, and the linking of imagery and action. *Quarterly Journal of Experimental Psychology*, *61*, 920–932. doi:10.1080/17470210701625626

Brooks, R. A. (1991). Intelligence without representation. *Artificial Intelligence*, *47*, 139–159. doi:10.1016/0004-3702(91)90053-M

Buccino, G., Binkofski, F., Fink, G. R., Fogassi, L., Gallese, V., Seitz, R. J., et al. (2001). Action observation activates premotor and parietal areas in a somatotopic manner: an fMRI study. *European Journal of Neuroscience*, *13*, 400–404. doi:10.1046/j.1460-9568.2001.01385.x

Carbonneau, K. J., Marley, S. C., & Selig, J. P. (2013). A meta-analysis of the efficacy of teaching mathematics with concrete manipulatives. *Journal of Educational Psychology*, *105*, 380–400. doi:10.1037/a0031084

Chi, M. T. H., Roy, M. & Hausmann, R. G. M. (2008). Observing tutorial dialogues collaboratively: Insights about human tutoring effectiveness from vicarious learning. *Cognitive Science, 32*, 301–341. doi: 10.1080/03640210701863396

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

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

Clark, A., & Chalmers, D. (1998). The extended mind. *Analysis*, *58*(1), 7–19.
Cook, S. W., Duffy, R. G., & Fenn, K. M. (2013). Consolidation and transfer of learning after observing hand gesture. *Child Development*, *84*, 1863–1871. doi:10.1111/cdev.12097
Cook, S. W., & Goldin-Meadow, S. (2006). The role of gesture in learning: Do children use their hands to change their minds? *Journal of Cognition and Development*, 7, 211–232. doi:10.1207/s15327647jcd0702_4
Cook, S. W., & Tanenhaus, M. K. (2009). Embodied communication: Speakers' gestures affect listeners' actions. *Cognition*, *113*, 98–104. doi:10.1016/j.cognition.2009.06.006
DeVega, M., Glenberg, A. M., & Graesser, A. C. (Eds.). (2008). *Symbols, embodiment and meaning: A debate*. Oxford, England: Oxford University Press.
Dreyfus, H. L. (2002). Intelligence without representation—Merleau-Ponty's critique of mental representation: The relevance of phenomenology to scientific explanation. *Phenomenology and the Cognitive Sciences*, *1*, 367–383. doi:10.1023/A:1021351606209
Feltz, D. L., & Landers, D. M. (1983). The effects of mental practice on motor skill learning and performance: A meta-analysis. *Journal of Sport Psychology*, *5*, 25–57. doi:10.1123/jsp.5.1.25
Fischer, U., Moeller, K., Bientzle, M., Cress, U., & Nuerk, H.-C. (2010). Sensori-motor spatial training of number magnitude representation. *Psychonomic Bulletin & Review*, *18*, 177–183. doi:10.3758/s13423-010-0031-3
Furuyama, N. (2000). Gestural interaction between the instructor and the learner in origami instruction. In D. McNeill (Ed.), *Language and gesture: Window into thought and action* (pp. 99–117). Cambridge, UK: Cambridge University Press. doi:10.1017/CBO9780511620850.007
Glenberg, A. M. (1997). What memory is for. *Behavioral and Brain Sciences*, *20*, 1–55. doi:10.1017/s0140525x97000010
Glenberg, A. M., Brown, M., & Levin, J. R. (2007). Enhancing comprehension in small reading groups using a manipulation strategy. *Contemporary Educational Psychology*, *32*, 389–399. doi:10.1016/j.cedpsych.2006.03.001
Glenberg, A. M., Gutierrez, T., Levin, J. R., Japuntich, S., & Kaschak, M. P. (2004). Activity and imagined activity can enhance young children's reading comprehension. *Journal of Educational Psychology*, *96*, 424–436. doi:10.1037/0022-0663.96.3.424
Glenberg, A. M., Jaworski, B., Rischal, M., & Levin, J. R. (2007). What brains are for: Action, meaning, and reading comprehension. In D. McNamara (Ed.), *Reading comprehension strategies: Theories, interventions, and technologies* (pp. 221–240). Mahwah, NJ: Lawrence Erlbaum Associates.
Glenberg, A. M., & Kaschak, M. P. (2002). Grounding language in action. *Psychonomic Bulletin & Review*, *9*, 558–565. https://doi.org/10.3758/BF03196313
Glenberg, A. M., & Robertson, D. A. (1999). Indexical understanding of instructions. *Discourse Processes*, *28*, 1–26. doi:10.1080/01638539909545067
Glenberg, A. M., Sato, M., Cattaneo, L., Riggio, L., Palumbo, D., & Buccino, G. (2008). Processing abstract language modulates motor system activity. *Quarterly Journal of Experimental Psychology*, *61*, 905–919. doi:10.1080/17470210701625550
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. doi:10.1037/0033-295X.100.2.279
Goldin-Meadow, S., Cook, S. W., & Mitchell, Z. A. (2009). Gesturing gives children new ideas about math. *Psychological Science*, *20*, 267–272. doi:10.1111/j.1467-9280.2009.02297.x
Hari, R., Forss, N., Avikainen, S., Kirveskari, E., Salenius, S., & Rizzolatti, G. (1998). Activation of human primary motor cortex during action observation: A neuromagnetic study. *Proceedings of the National Academy of Sciences*, *95*, 15061–15065. doi:10.1073/pnas.95.25.15061
Hauk, O., Johnsrude, I., & Pulvermüller, F. (2004). Somatotopic representation of action words in human motor and premotor cortex. *Neuron*, *41*, 301–307. doi:10.1016/S0896-6273(03)00838-9
Hostetter, A. B., & Alibali, M. W. (2008). Visible embodiment: Gestures as simulated action. *Psychonomic Bulletin & Review*, *15*, 495–514. doi:10.3758/PBR.15.3.495
Johnson-Glenberg, M. C., Birchfield, D. A., Tolentino, L., & Koziupa, T. (2013). Collaborative embodied learning in mixed reality motion-capture environments: Two science studies. *Journal of Educational Psychology*, *106*, 86–104. doi:10.1037/a0034008.supp
Kang, S., & Tversky, B. (2016). From hands to minds: Gestures promote understanding. *Cognitive Research: Principles and Implications*, *1*, 4. doi:10.1186/s41235-016-0004-9
Kita, S., Alibali, M. W., & Chu, M. (2017). How do gestures influence thinking and speaking? The gesture-for-conceptualization hypothesis. *Psychological Review*, *124*, 245–266. doi: 10.1037/rev0000059
Lakoff, G., & Johnson, M. (1999). *Philosophy in the flesh: The embodied mind and its challenge to Western thought*. New York: Basic Books.
Lee, V. R. (Ed.). (2015). *Learning technologies and the body: Integration and implementation in formal and informal learning environments*. New York: Routledge.

Lindgren, R., & Johnson-Glenberg, M. (2013). Emboldened by embodiment: Six precepts for research on embodied learning and mixed reality. *Educational Researcher*, *42*(8), 445–452. doi:10.3102/0013189X13511661

Lindgren, R., Wallon, R. C., Brown, D. E., Mathayas, N., & Kimball, N. (2016). "Show me" what you mean: Learning and design implications of eliciting gesture in student explanations. In C.-K. Looi, J. Polman, U. Cress, & P. Reimann (Eds), *Transforming learning, empowering learners: The International Conference of the Learning Sciences (ICLS) 2016* (Vol. *2*, pp. 1014–1017). Singapore: International Society of the Learning Sciences.

Martin, T., & Schwartz, D. L. (2005). Physically distributed learning: Adapting and reinterpreting physical environments in the development of fraction concepts. *Cognitive Science*, *29*, 587–625. doi.10.1207/s15516709cog0000_15

Nathan, M. J., & Martinez, C. V. J. (2015). Gesture as model enactment: The role of gesture in mental model construction and inference making when learning from text. *Learning: Research and Practice*, *1*, 4–37. doi:10.1080/23735082.2015.1006758

Nathan, M. J., & Walkington, C. A. (2017). Grounded and embodied mathematical cognition: Promoting mathematical insight and proof using action and language. *Cognitive Research: Principles and Implications*, 2:9. doi 10.1186/s41235-016-0040-5

Nathan, M. J., Walkington, C., Boncoddo, R., Pier, E., Williams, C. C., & Alibali, M. W. (2014). Actions speak louder with words: The roles of action and pedagogical language for grounding mathematical proof. *Learning and Instruction*, *33*, 182–193. doi:10.1016/j.learninstruc.2014.07.001

Nemirovsky, R., & Ferrara, F. (2008). Mathematical imagination and embodied cognition. *Educational Studies in Mathematics*, *70*, 159–174. doi:10.1007/s10649-008-9150-4

Ottmar, E., & Landy, D. (2017). Concreteness fading of algebraic instruction: Effects on learning. *Journal of the Learning Sciences*, *26*, 51–78.

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

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

Ping, R., Goldin-Meadow, S., & Beilock S. (2014). Understanding gesture: Is the listener's motor system involved? *Journal of Experimental Psychology: General*, *143*, 195–204. doi:10.1037/a0032246

Pouw, W. T. J. L., van Gog, T., & Paas, F. (2014). An embedded and embodied cognition review of instructional manipulatives. *Educational Psychology Review*, *26*, 51–72. doi:10.1007/s10648-014-9255-5

Richland, L. E. (2015). Linking gestures: Cross-cultural variation during instructional analogies. *Cognition and Instruction*, *33*, 295–321. doi:10.1080/07370008.2015.1091459

Rizzolatti, G., Fogassi, L., & Gallese, V. (2001). Neurophysiological mechanisms underlying the understanding and imitation of action. *Nature Reviews Neuroscience*, *2*, 661–670. doi:10.1038/35090060

Robbins, P., & Aydede, M. (2009). A short primer on situated cognition. In P. Robbins & M. Aydede (Eds.), *The Cambridge handbook of situated cognition* (pp. 3–10). Cambridge, England: Cambridge University Press.

Rummel, N., & van Gog, T. (2018). Example-based learning, In F. Fischer, C. E. Hmelo-Silver, S. R. Goldman, & P. Reimann (Eds.), *International handbook of the learning sciences* (pp. 201–229). New York: Routledge.

Shapiro, L. (2011). *Embodied cognition*. New York: Routledge.

Singer, M. A., & Goldin-Meadow, S. (2005). Children learn when their teacher's gestures and speech differ. *Psychological Science*, *16*, 85–89. doi:10.1111/j.0956-7976.2005.00786.x

Tettamanti, M., Buccino, G., Saccuman, M. C., Gallese, V., Danna, M., Scifo, P., et al. (2005). Listening to action-related sentences activates fronto-parietal motor circuits. *Journal of Cognitive Neuroscience*, *17*, 273–281. doi:10.1162/0898929053124965

Thomas, L. E., & Lleras, A. (2007). Moving eyes and moving thought: On the spatial compatibility between eye movements and cognition. *Psychonomic Bulletin & Review*, *14*, 663–668. doi:10.3758/BF03196818

van Dam, W. O., Rueschemeyer, S.-A., & Bekkering, H. (2010). How specifically are action verbs represented in the neural motor system: An fMRI study. *NeuroImage*, *53*, 1318–1325. doi:10.1016/j.neuroimage.2010.06.071

Wallon, R. C., & Lindgren, R. (2017). Cued gestures: Their role in collaborative discourse on seasons. In B. K. Smith, M. Borge, E. Mercier, & K. Y. Lim (Eds.), *Making a difference: Prioritizing equity and access in CSCL, 12th International Conference on Computer Supported Collaborative Learning (CSCL) 2017* (Vol. *2*, pp. 813–814). Philadelphia, PA: International Society of the Learning Sciences.

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