2 Embodied Concepts: Basic Mechanisms and Their Implications for Learning and Memory

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According to Piaget's theory of cognitive development, children acquire knowledge through sensory experiences and the manipulation of objects until the age of two. After learning to use symbols (e.g., words, pictures) to represent and think about objects and events, children are thought to develop logical thinking, which is still based on concrete events between the ages of seven and eleven (Piaget, 1952). Formal logical thinking detached from sensorimotor experiences, the highest level of cognition, is assumed to develop later during adolescence. According to this theory, formal logical thinking replaces thinking based on sensory and motor processes (Inhelder & Piaget, 1958). At that stage of development, thought operations do not need to relate to concrete experiences and phenomena. The question whether this theory holds is of high relevance for the design of school lessons. At present, teachers often follow the implications of Piaget's model: in primary school, discovery learning and experiential learning activities are common instructional strategies for active learning arrangements. By contrast, in secondary schools these teaching strategies are less common. Often they are limited to active phases in natural science classes (if they occur at all).

Consider a classroom situation in which a teacher wants to introduce an unfamiliar musical instrument, a bassoon, to her or his students. She or he has several possibilities for teaching the relevant information. For instance, (1) the teacher can verbally describe the shape, the material, the sound, and the use of this musical instrument. (2) The teacher could show a movie demonstrating the physical properties, the sound, and the use of a bassoon. (3) The teacher could take the students to an orchestra where they can observe a musician playing the bassoon and can touch or play the bassoon themselves. In this case, perceptual and motor information elicited by the direct experience are the basis of knowledge building. The different methods to teach a bassoon may be differentially efficient in supporting learning. It would be therefore important to know which methods have the most beneficial effects and why (Kiefer & Trumpp, 2012).

From Amodal over Embodiment to Hybrid Theories of Conceptual Representations

Psychological and neuroscientific research provides information on the relationship between sensorimotor processes and abstract cognitive processes. At the heart of the past and the current debates is whether cognition is essentially grounded in our senses and in our actions with the environment (Markie, 2008). Traditionally, cognition is assumed to involve neurocognitive systems that are different from the perceptual or motor brain systems and code knowledge in an abstract-symbolic format, in which original modality-specific sensorimotor information is lost (Anderson, 1983; Pylyshyn, 1984; Quillian, 1969; Tyler & Moss, 2001). This resembles the stage of formal logical thinking in Piaget's classical theory (Inhelder & Piaget, 1958), as outlined earlier.

At an anatomical level, amodal conceptual representations are assumed to be held in heteromodal association cortex such as the anterior temporal (McClelland & Rogers, 2003; Rogers et al., 2004) or posterior temporal cortex (Hoffman et al., 2012), so-called semantic hubs. Although some traditional amodal theories do not deny the involvement of the sensory and motor systems in conceptual tasks, they assume that activation of modality-specific representations during language comprehension or conceptual thinking is only a concomitant process after the amodal concept has been accessed, due to imagery (Machery, 2007) or passive spreading of activation to input or output levels (Mahon, 2015).

Challenging this classic view, recent theories of embodied cognition, which are also known as "grounded" or "situated" cognition theories, have emerged in several disciplines of the cognitive sciences (Barsalou et al., 2018; Kiefer & Barsalou, 2013; Kiefer & Harpaintner, 2020; Lakoff & Johnson, 1999; Pulvermüller & Fadiga, 2010). Embodiment theories propose close links between the sensory and motor brain systems on the one hand and cognition on the other hand (Kiefer & Trumpp, 2012). Cognition and thinking is critically based on a reinstatement of external (perception) and internal states (proprioception, emotion, and introspection) as well as bodily actions that produce simulations of previous experiences. These simulations of previous sensorimotor experiences (Kiefer & Barsalou, 2013) are often unconscious but can be measured with behavioral or neuroscientific experimental techniques (Trumpp et al., 2013).

Most recent evidence suggests an interplay between modality-specific, bimodal or trimodal, multimodal and amodal semantic hub regions, giving rise to the development of so-called hybrid theories (Kiefer & Harpaintner, 2020; Kuhnke et al., 2020; Patterson & Ralph, 2016; Popp et al., 2019). Modality-specific and multimodal regions presumably represent conceptual feature content (Kuhnke et al., 2020), whereas semantic hubs code conceptual information in an overarching supramodal fashion (Binder, 2016). Most likely, a hierarchy of processing circuits (ranging from lower-level modality-specific cortex over multimodal regions up to top-level amodal areas in heteromodal cortex, indexing increasing levels of abstraction) establishes conceptual representations (Kiefer & Harpaintner, 2020; Kuhnke et al., 2020). In the next sections, we provide a comprehensive overview of the latest research on embodied cognition in several cognitive domains and discuss important implications for learning and teaching.

Embodiment of Memory for Events

Past events such as incidences associated with our last birthday are stored in episodic memory, the long-term memory system for events (Tulving, 1972). When we recall these events, not only do we recall abstract-symbolic verbal knowledge, but we also reactivate stored sensorimotor experiences collected during the initial learning episode (Engelkamp & Jahn, 2003). These reactivations of acquired sensorimotor memory traces are not epiphenomenal but are essential for memory performance.

The so-called enactment effect nicely illustrates the importance of rich sensorimotor experiences (Engelkamp & Jahn, 2003): Participants remembered a list of action verbs better when they performed the corresponding actions in the learning phase, compared with a condition when they simply read the words. Observing others who performed the action also improved subsequent memory compared with reading, but it was inferior to self-performed actions (Senkfor, et al., 2002). Neurophysiological recordings of brain activity during memory recall revealed an activation of motor areas only for self-performed actions during learning (Senkfor et al., 2002), suggesting that action representations established during word learning were reactivated and facilitated memory retrieval. Reactivations of stored experiences in modality-specific brain areas (i.e., areas specifically engaged in perception or action) during memory retrieval are not only observed for self-performed actions but also for sensory information such as vision or sound associated with the learning episode (Ranganath et al., 2004). This finding shows that episodic memory is multimodal in its essence because it is based on a reinstatement of sensory and motor experiences (Engelkamp & Jahn, 2003).

Establishing the relevant sensory and motor memory traces during learning therefore improves subsequent memory performance compared with pure verbal learning. These results suggest that teaching strategies such as (language) learning through drama, “experiments,” and outdoor activities are suitable to support the building of memory by providing multimodal information (e.g., science learning; Uysal & Yavuz, 2018). Moreover, the enactment effect indicates that vocabulary training of action verbs can be improved by the corresponding movements.

Embodiment of Conceptual Memory for Objects

Concepts held in semantic long-term memory (Tulving, 1972) include the sum of our sensory and motor experiences with the environment in a categorical fashion (Kiefer & Pulvermüller, 2012). For instance, the concept “bassoon” includes the information that a bassoon has a long shape, is made of wood, produces sound, and is a wind instrument. It is an important question whether even concepts—the abstract constituents of thought—are grounded in perception and action.

Neuroimaging results (for an overview, see Kiefer & Barsalou, 2013) have provided converging evidence on the differential involvement of sensorimotor brain areas in the processing of words and concepts of different kinds (e.g., vision-related concepts versus action-related concepts). When processed, these words elicited activity in sensorimotor brain areas in a range of conceptual tasks (Hoenig et al., 2008; Simmons et al., 2005). In fact, conceptual and perceptual processing functionally and neuroanatomical overlaps in sensory brain regions: Visual recognition of words denoting objects, for which acoustic features are highly relevant (e.g., sound-related concepts such as “telephone”), ignited cell assemblies in auditory brain regions that were also activated by sound perception (Kiefer et al., 2008). Processing of action words (e.g., “to throw”) elicited activity in motor areas (Hauk et al., 2004), partially overlapping with activity induced by real movements of the corresponding limb (e.g., hand-related movements).

Functional magnetic resonance imaging studies (Kuhnke et al., 2020; Popp et al., 2019), however, have indicated that not only modality-specific brain areas as defined by localizer tasks (e.g., acoustic localizer: listening to sounds; motor localizer: moving the hands) but also adjacent higher-level multimodal regions respond to concepts with a high relevance of a given feature type (e.g., acoustic or action features). Activity in both modality-specific and multimodal regions was modulated by task demands, indicating conceptual flexibility at various levels of the conceptual processing hierarchy. As already outlined at the beginning of this chapter, a hierarchy of processing circuits establishes conceptual representations (Kiefer & Harpaintner, 2020; Kuhnke et al., 2020;

Popp et al., 2019). These findings thus support hybrid models of conceptual representations combining assumptions of modal embodiment theories with those of amodal theories (Kiefer & Pulvermüller, 2012; Patterson & Ralph, 2016).

Conceptual memory traces in sensorimotor areas are established through the learning-based formation of cortical cell assemblies as a direct consequence of the experience with the referent. One line of evidence comes from training studies on the experience-dependent acquisition of concepts for novel objects (T. W. James & Gauthier, 2003; Kiefer et al., 2007). For instance, human participants learned concepts of novel objects ("nobjects") under different training conditions (Kiefer et al., 2007): the participants either made an action pantomime toward a detail feature of the novel object, which signaled a specific object function, or pointed to it. During the test, only for the pantomime group—in which a meaningful action was performed toward the object during training—was there early activation in frontal motor regions and later activation in occipitoparietal visuomotor regions during conceptual processing, indicating that action representations essentially constitute the concept. In the pointing group, in which the action during training was not meaningfully related to the object, this sensorimotor activity was absent, suggesting that concepts were not grounded in action.

The second line of evidence comes from studies investigating experience-dependent formation of conceptual representations in experts with real objects. For instance, only professional musicians, but not musical laypersons, activate the auditory association cortex when accessing conceptual knowledge about musical instruments (Hoenig et al., 2011). Together with similar expertise studies (Beilock et al., 2008; Lyons et al., 2010), these findings confirm that the grounding of concepts in the sensorimotor circuits of the brain is the result of repeated meaningful interactions with the referent. If this experience is lacking, concepts are less rich and are mainly based on verbal associations (Solomon & Barsalou, 2004). In fact, we found that deaf individuals, who could not rely on the auditory input channel since early childhood, recruited language brain systems more strongly than hearing individuals (Trumpp & Kiefer, 2018). This study also showed that deaf individuals compensated for the loss of the auditory channel by additional recruitment of visual and motor areas.

Returning to the bassoon example, when confronted with the name "bassoon," for instance, a musical layperson or a deaf individual may be able to retrieve other words typically co-occurring with the word "bassoon," such as "musical instrument," "orchestra," or "violin," without having a clear grasp what a bassoon really is or how it sounds. In contrast, musical experts have profound experience and knowledge about the shape of a bassoon, its sound, and the actions need to play this instrument. This notion of experience-dependent plasticity of conceptual representation supports teaching approaches like scenic learning in foreign language teaching, in which vocabulary training is accompanied by meaningful gestures and movements not only for action word but also for nouns (Macedonia & Klimesch, 2014).

Embodiment of Conceptual Memory for Numbers

Although the embodiment of object concepts may be intuitive to some extent, it is less obvious how abstract concepts such as numbers, which do not have a clear physical referent, are grounded in perception and action. Nevertheless, several lines of evidence show that processing number concepts (e.g., knowing that 6 is greater than 4) involves the sensorimotor systems similar to concrete object concepts.

First, accessing number magnitude depends on a mental number line, which resembles visuospatial representations (Dehaene, 1992). Behavioral number comparison experiments (e.g., deciding which digit is larger, 6 or 2) provide objective evidence for the existence of an analogue mental number line that has a logarithmic scale similar to the mental representation of the size or intensity of sensory stimuli (Nieder, 2005). Furthermore, neuroimaging studies consistently have shown that number magnitude is represented in a parietal area (intraparietal sulcus) that is also involved in processing space (Nieder, 2005).

Second, in addition to visuospatial representation, numbers are grounded in the motor system, particularly in hand actions (Lindemann et al., 2007). Most impressively, finger counting systems used in childhood to learn numbers still play a role in adults when they process numbers. Intercultural studies have shown that reaction times in a number comparison experiment are strongly influenced by the finger-counting habits typically used in a given culture (Domahs et al., 2010). Only for German participants, who use unimanual finger counting habits for numbers up to five and bimanual habits for numbers greater than five, were number comparisons slower when they involved numbers both below and above five (i.e., numbers that require one versus two hands in the German finger-counting system). In Chinese participants, who use a unimanual symbolic finger counting system for these numbers, this effect was absent. In line with developmental studies demonstrating the importance of finger recognition in childhood for later arithmetic abilities (Noel, 2005), this study showed that fairly abstract number concepts are at least partially rooted in our motor experiences. In line with this documented association between numbers and finger counting, enhanced activity in the motor cortex was observed when number concepts were processed (Tschentscher et al., 2012).

Hence, number concepts appear to be embodied in both visuospatial and action-related representations. Explicitly training children in finger counting as well as in spatial analogues of number magnitude accelerates learning numbers and has beneficial effects on subsequent mathematical performance even in students' later school or professional career (see Fischer et al., 2011).

Embodiment of Memory for Abstract Concepts

By definition, abstract concepts do not refer to physical objects that can be directly experienced by the senses. The representation of abstract concepts, such as abstract ideas or scientific theories, imposes challenges for all classes of theories of conceptual representation (see also Dove, 2016). Abstract concepts are more complex and ambiguous than concrete concepts because they apply to rather heterogeneous situations (Barsalou & Wiemer-Hastings, 2005; Hoffman et al., 2013). Therefore, all theories have to deal with a high degree of conceptual flexibility. Abstract concepts are a particular challenge for embodied cognition theories because at first glance it is hard to imagine how concepts without a referent that can be perceived or acted on could be grounded in the sensory and motor brain systems (Dove, 2009, 2016).

Past research was dominated for a long time by the view that abstract concepts require amodal, symbolic (Mahon & Caramazza, 2009), or verbal representations (Paivio, 1986). In Paivio's dual coding theory (1986), abstract concepts were thought to be stored in a verbal-symbolic code, whereas concrete concepts relied on both a visual imaginary and a verbal-symbolic code.

In the recent years, however, in order to account for the representation of abstract concepts, embodied cognition theories have been refined. We and others have suggested that abstract concepts might be grounded not only in the perception of external events such as situations, but also in the introspection of internal mental states and in mentalizing social constellations (Barsalou & Wiemer-Hastings, 2005; Borghi & Binkofski, 2014; Harpaintner et al., 2018; Kiefer & Barsalou, 2013) or in processing affective states (Kousta et al., 2011).

Refined embodied cognition theories have been confirmed by several lines of research that indicate that abstract concepts depend not only on the verbal system but also on a variety of modal systems, including perception, action, emotion, and introspection (for reviews, see Borghi et al., 2017; Kiefer & Harpaintner, 2020). A property listing study (Harpaintner et al., 2018) revealed that participants generated a substantial proportion of introspective, emotional, and social properties in addition to verbal associations. In terms of quantity, however, sensory and motor properties played the most crucial role in this study. The broad diversity in the participants' listings was consistent with refined grounded cognition theories, showing that the semantic content of abstract concepts includes various semantic features. These results also suggest that only one relatively small subgroup of abstract concepts is predominantly related to verbal associations.

In line with this property listing study, neuroimaging studies have identified activity areas related to emotions (Vigliocco et al., 2014), mental states (Wilson-Mendenhall et al., 2013), and social interactions (Wilson-Mendenhall et al., 2013) when abstract concepts are processed. Furthermore, similar to concrete concepts, subgroups of abstract concepts have been shown to activate visual and motor areas also involved in perception and action (Harpaintner et al., 2020). For example, abstract physical concepts related to periodicity (e.g., "frequency") activated postcentral and parietal brain regions—regions found to be active when performing rhythmic movements (Mason & Just, 2016).

Hence, in contrast to Piaget's view that scientific or mathematical concepts essentially build upon abstract formal logical reasoning (Inhelder & Piaget, 1958), the findings reviewed here show that even fairly abstract concepts are grounded in modal systems including emotions, introspection, perception, and action. We assume that such a grounding in experiences is necessary for a deep understanding of abstract concepts, whereas knowledge is superficial when only based on verbal instruction. We therefore propose that abstract concepts should be taught by providing learners with meaningful visualizations or movements.

Embodiment of Reading and Writing

Writing is a manual sensorimotor skill that requires the acquisition and storage of complex motor programs. For reading, its grounding in the sensorimotor systems is less obvious, because reading is typically considered to be purely perceptual (e.g., McClelland & Rumelhart, 1981). However, embodiment theory predicts that reading is influenced by writing techniques because the motor programs and sensory experiences during writing (e.g., forming specific letters and words with a pen) are assumed to be implicitly activated during reading. As a consequence, our habitual writing techniques should affect reading performance.

It is particularly important to consider this possible relation between reading and writing because nowadays digital writing devices associated with the use of mobile phones, tablets, or computers have frequently replaced writing by hand (for an overview, see Kiefer & Velay, 2016). The sensorimotor experiences during handwriting (haptic, motor, visual, etc.) are quite different from those during typewriting or mouse clicking on digital devices. In particular, handwriting requires carefully reproducing the shape of each letter, whereas in typewriting no such graphomotor component is present. Given that modern children may learn writing by typing on a computer or mobile phone long before they master handwriting, it is important to know how this dramatic change in writing habits affects reading performance (Mangen & Balsvik, 2016).

Consistent with embodiment theory, several training studies in preschool children and adults have shown that handwriting training of new letters gave rise to a better letter recognition in a subsequent test than typing training (e.g., Longcamp et al., 2005). This demonstrates that handwriting, which links rich sensorimotor representations to perceptual letter shapes, improves subsequent letter reading performance compared with typewriting. In line with this interpretation, neuroimaging studies showed that visual recognition of letters only activated motor regions of the brain when letters were trained by handwriting, but not when they were trained by typewriting (K. H. James & Engelhardt, 2012). The authors confirmed the assumption that sensorimotor experiences must be meaningfully related to the learning target (here, shaping a letter by writing versus pressing a key associated with a letter) to result in stronger sensorimotor memory traces that facilitate learning.

Although several behavioral and neuroimaging intervention studies seem to suggest a superiority of handwriting training over typing training on subsequent reading and writing performance in young children, other evidence has been mixed. Improved letter recognition after handwriting training compared with typing training was not always replicated (Kiefer et al., 2015). Unfortunately, the effects at the word level are also heterogeneous: the superiority of handwriting over typing training on word writing performance (Cunningham & Stanovich, 1990; Kiefer et al., 2015) was not found in other studies (Ouellette & Tims, 2014; Vaughn et al., 1992).

Mayer and colleagues (2020) therefore examined the influence of a writing tool on the acquisition of literacy skills at the letter and word level with various tests in a large sample of kindergarten children ($n = 147$). Using closely matched letter learning games, children were trained with sixteen letters by handwriting with a pencil on a sheet of paper, by writing with a stylus on a tablet computer, or by typing letters using a virtual keyboard on a tablet across seven weeks. Training using a stylus on a touch screen was an interesting comparison condition for traditional handwriting because the slippery surface of a touch screen had lower friction than paper and thus increased difficulty of motor control. Visuospatial skills were also assessed to test whether the different training regimens affected cognitive domains other than written language. Children of the pencil group showed superior performance in letter recognition and improved visuospatial skills compared with keyboard training. Keyboard training, however, resulted in superior performance in word writing and reading compared with handwriting training with a stylus on the tablet, but not compared with the pencil group.

Our results suggest that handwriting with a pencil fosters acquisition of letter knowledge and improves visuospatial skills compared with keyboarding. At least given the current technological state, writing with a stylus on a touch screen seems to be the least favorable writing tool, possibly because of the increased demands on motor control. Writing training with a stylus on a tablet led to inferior reading and writing performance at the word level compared with keyboarding. At the same time, the beneficial effects of handwriting training on letter recognition and visuospatial skills were less pronounced compared with writing with a pencil.

Conclusion

The role of Piaget's theory in the classroom has been discussed since the 1960s (Benz et al., 2015). The reception of this theory contributed substantially to the abandonment of the assumption that children's minds are qualitatively similar to adult minds and work in a similar manner (Smith, 1987). This led to changes in school curricula. More active, self-regulated learning phases were integrated into the lessons. Unfortunately, this important contribution to improving the quality of teaching was limited to preschool and primary school. Based on Piaget's stage model, secondary school students acquire knowledge on the basis of formal cognitive operations (i.e., in the way that adults subjectively perceive themselves). Subjective self-perception, however, does not correspond to current research findings.

According to the latest research reviewed here, cognition is grounded in perception and action, and even the most complex and abstract thoughts are sense-based and not abstract-symbolic. There are examples from many cognitive domains showing that *appropriate* sensorimotor experiences are necessary for human cognition to develop at the highest level. Therefore, embodied cognition theory is naturally highly relevant for many issues associated with education (Kiefer & Trumpp, 2012; O'Loughlin, 2006). Embodied cognition theory highlights the relevance of experiential interactions with our environment during learning, resulting in more endurable and—perhaps most important—richer knowledge. These experiences frequently include perception and action but may also reflect introspection of emotional and other mental states.

Returning the example of learning a bassoon at the beginning, according to a symbolic view of cognition it would be sufficient for the teacher to verbally describe aspects such as the shape, the sound, and the material of a bassoon in a written text, perhaps complemented by a picture. A direct experience with the object would not be necessary. According to embodiment theories, rich knowledge about the unfamiliar bassoon can only be acquired when the students can see, hear, touch, and act on the bassoon. A pure verbal description should result in impoverished, less durable knowledge. As human cognition is the basis for thought, language, and action, rich embodied knowledge about our physical and social world is highly important for the developing mind, educational success, and thus for the functioning of our society.

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