CHAPTER

24

The Perceptual Representation of Mental Categories

Diane Pecher

Abstract

Many studies have shown that mental categories share processing mechanisms with perception and action. According to a strong view of grounded cognition, these sensory-motor mechanisms are sufficient for mental representations, while more moderate views might say that other, more abstract mechanisms also play a role. Several lines of research support the idea that mental categories are grounded in sensory-motor processes. Behavioral studies show interactions between cognition and perception or action, suggesting that they share mechanisms. Neuroscientific studies have collected evidence that sensory-motor brain areas are involved in cognition. Several connectionist models show how sensory-motor experiences can be combined and result in categorical representations. These findings suggest a highly flexible and interactive system in which the strict distinction between sensory-motor processing and other types of processing may no longer be relevant.

Key Words: grounded cognition, concepts, sensory-motor simulation

Many categories in the world have perceptual qualities that allow us to recognize and interact with them. We recognize apples by their shape and color, and when we eat an apple we recognize the feel in our hand, the texture of skin and flesh when we bite, and the taste and smell of the fruit. But what about the categories in our minds? Do they also have perceptual qualities, and if they do, to what extent do we use these perceptual qualities to categorize, make inferences and predictions, and, in short, to think? This chapter discusses some recent theories that have proposed that the mental representation of categories shares processing mechanisms with perception and action.

Perceptual Theories of Concepts

The starting point for this chapter is the assumption that most of our mental categories are relevant to us because they allow us to perceive our environment and perform actions (Glenberg, 1997). The most influential theory on the role of perception for mental categories is Barsalou's (1999) Perceptual Symbols theory. Perceptual symbols are the neural states that underlie perception and action. The perceptual symbols that represent categories are learned through recurrent experiences of perceiving and interacting with exemplars. These experiences are captured by modality-specific sensory-motor systems and integrated via hierarchical association areas (Barsalou, 2008; Barsalou, Simmons, Barbey, & Wilson, 2003). At the perceptual level are the modality-specific activations that represent the states of sensory-motor systems. At this level, association areas connect the neuronal patterns that resulted from a specific experience in order to capture such states. Higher level cross-modal association areas then integrate these modality-specific patterns into multimodal experiences. These association networks represent categorical knowledge that can be recruited for cognitive processing. Mental representation of a category is achieved by simulators that reactivate aspects of experience in a top-down fashion from higher level association areas back to the modality-specific sensory-motor systems.

Such mechanism might be achieved by connectionist networks, in which simple processing units are highly interconnected. In such connectionist networks, experiences or categories are represented by activation patterns across the units. Learning takes place by adjustments of the strength of connections between units. Through repeated activation of a pattern the connections between units that are activated simultaneously become stronger and the whole pattern becomes an attractor. An attractor is a stable state of the network in which energy is low. An important characteristic of such attractors is that when the pattern is only partially activated, the network can complete the pattern by a process of iterative spreading activation. Because strength of the connection between units determines how much they activate (or inhibit) each other, and units that were part of the same pattern have strong connections, the previously learned pattern is recovered in a number of updating cycles in which the activation level of each unit is adjusted according to the activation levels of the other units and the strength of the connections between the units (e.g., Masson, 1995; McRae, Cree, Westmacott, & de Sa, 1999; McRae, de Sa, & Seidenberg, 1997; Plaut, 2002; Pulvermüller, 1999). A simulator might work the same way by completing patterns of activation in sensory-motor systems in order to represent experiential knowledge.

Several other theories have also proposed that concepts are grounded in sensory-motor processing (Glenberg, 1997; Prinz, 2002; Pulvermüller, 1999). It is important to note that the actual representation is achieved by the sensory-motor systems and not by the higher level association areas, and that this aspect of the theory is essentially different from a symbolic account of cognition, which would assume that abstract representations suffice for categories. A middle position was proposed by Mahon and Caramazza (2008), who argue that sensory-motor systems enrich representations, but that categories are at least partially abstract. Before looking at specific models I will first review the studies that have contributed to the idea that sensory-motor simulations and mental categories are strongly associated.

Researchers should always be hesitant to claim that particular results provide conclusive *evidence* for a theory. As various authors (e.g., Dove, 2009; Mahon & Caramazza, 2008) have noted, showing sensory-motor effects does not necessarily entail that all representations consist purely of sensory-motor simulations. Rather, sensory-motor simulations may be only part of a representation, or even a mere by-product of representation. Providing conclusive evidence might be extremely difficult, similar to the difficulties associated with distinguishing exemplar and prototype models of categorization. In exemplar models, each experience with a category is stored, and abstractions are computed at the time of retrieval by combining a whole set of exemplars (Hintzman, 1986; Nosofsky, 1988). In contrast, prototype models assume that category abstractions (prototypes) are stored in memory. These models make almost identical predictions because it is impossible to distinguish between stored and computed abstractions (Barsalou, 1990; Murphy, 2002). For the sake of parsimony one might therefore favor the exemplar model approach. A similar situation exists for the distinction between fully grounded and partially grounded theories of cognition. Thus, one should be careful to interpret evidence for sensory-motor simulations as support for the fully grounded view. On the other hand, in the absence of decisive evidence, a fully grounded view might be more parsimonious and therefore preferable.

Evidence for Perceptual Simulation

Representation and Perception of Categories Interact

Grounded theories argue that sensory-motor simulations underlie representations of categories. In this view, a category, for example, apple, is represented by simulation of an experience with an apple, such as seeing a round, red object, which can be grasped by one hand and feels firm, is sweet, tart, and juicy when bitten, and so on. Because the simulation is supported by sensory-motor systems, there should be interactions between representational processes and perceptual processes. An important line of evidence comes from studies that show effects of mental representation on processing of visual stimuli. The idea is that representation of a category and perception of a category used (partly) overlapping perceptual features, which are then processed more easily when they are activated by two sources. For example, in a series of studies Zwaan and colleagues (Stanfield & Zwaan, 2001; Zwaan, Madden, Yaxley, & Aveyard, 2004; Zwaan, Stanfield, & Yaxley, 2002) showed that sentences in which an object's orientation, shape, or motion was implied (e.g., *He hammered the nail into the floor* vs. *He hammered the nail into the wall*) affected the speed of picture processing in which the relevant dimension either matched or mismatched the sentence (e.g., a picture of a nail oriented horizontally or vertically). Connell (2007) showed similar effects for color. Thus, processing is affected by the overlap in perceptual features between representation and perception.

The effect of such overlap might be due to task-induced strategies. When linguistic stimuli and perceptual stimuli are alternated and the task involves comparison of two consecutive stimuli, participants may be induced to consciously generate images of the objects described by the sentences. Therefore, the effects may reflect strategic rather than automatic activation of perceptual information. To circumvent this problem, Pecher, van Dantzig, Zwaan, and Zeelenberg (2009) presented all sentences blocked, and after a delay, all pictures were presented. Thus, during sentence processing participants did not know yet that they would see pictures of the objects that were mentioned in the sentences. Recognition performance was still better for matching than mismatching pictures even 45 minutes after reading the sentences. Thus, implied orientation and shape are not only represented during online language processing but also affect representations at longer delays. Both short- and long-term effects indicate that the mental representations of categories not only contain perceptual features but also that the particular features that are represented (e.g., orientation) are context dependent.

Representation Has Perceptual Qualities

The representation of categories by sensory-motor systems implies that these representations retain perceptual qualities. Several studies have shown that the representation of categories itself is influenced by variables that are perceptual in nature, even if the stimuli themselves are words and do not contain any perceptual information of their referents. Solomon and Barsalou (2001) asked participants to verify, for example, whether *a horse has mane*. Earlier in the experiment the same property had been presented with a different category. The critical manipulation was whether the property has a similar perceptual form on the context trial (e.g., *pony-mane*) or a different perceptual form (e.g., *lion-mane*). They showed that performance was better if the context and target property had a similar form than if they did not. Priming for shape similarity (e.g., *banjo-tennis racket*) has also been observed in tasks that require less semantic processing such as word naming and lexical decision (Pecher, Zeelenberg, & Raaijmakers, 1998), although the effect tends to be quite fragile in such tasks. Thus, overlap in perceptual features facilitates processing. This effect of shape similarity indicates that participants have visual representations of categories.

Other studies have shown effects of visual perspective. Solomon and Barsalou (2004) showed that verification times for object-property word pairs were affected by perceptual variables such as the relative size and location of the property on the object. Wu and Barsalou (2009) asked participants to generate properties for objects that were presented in isolation (*watermelon*) or with a modifier that changed which properties would be visible if the object were actually present (*half watermelon*). Visible properties were more likely to be generated than occluded properties. For example, the property *seeds* was generated more often for *half watermelon* than for *watermelon* without modifier. Borghi, Glenberg, and Kaschak (2004) presented sentences that invoked a particular perspective (*You are driving a car* vs. *You are washing a car*) and subsequently asked participants to verify properties. Performance in the property verification task was affected by whether the property was visible from the particular perspective invoked by the sentence (e.g., *tires*, *steering wheel*).

Of course, categories are not only represented visually. Action and other sensory modalities also contribute to representation. Pecher, Zeelenberg, and Barsalou (2003) demonstrated that, just as in perceptual tasks (Spence, Nicholls, & Driver, 2001), switching between sensory modalities in conceptual judgments incurred a processing cost. Category names were presented with a property name from a specific modality in a property verification task. Responses were faster and more accurate if a target trial (e.g., *apple-red*) was preceded by a context trial from the same modality (e.g., *diamond-sparkling*) than if it was preceded by a context trial from a different modality (e.g., *airplane-noisy*). The explanation for this effect is that when participants perform the property verification task, they simulate experiencing an exemplar from the category in such a way that they can observe whether the exemplar has the property. In that way, they focus their attention on the relevant modality. A switching cost occurs because when the next pair is presented, attention is still focused on the modality that was relevant for the previous trial. The modality-switch effect has been replicated (Marques, 2006) and extended to switching between affective and perceptual representations (Vermeulen, Niedenthal, & Luminet, 2007). In addition to the modality-switch effect, Marques showed that performance was not affected by switching between superordinate categories. He presented animals and artifacts with modality-specific features. Whereas performance was affected by switching modalities (e.g., *mirror-reflect*, *telephone-ring*), there was no effect of superordinate switching (e.g., *donkey-heehaw*, *telephone-ring*). These results strongly suggest that categories are represented by perceptual modalities rather than by hierarchical domains.

Finally, there is an important role of action for representing categories. Since the main function of categories is to support our interactions with the environment, action should be central to representations. That this is very likely the case is demonstrated by the interaction between representation and action. When interacting with objects, the first action is often to touch the object. Therefore, grasping and pushing actions might be strongly activated. Having the hand in the appropriate shape to grasp a particular object facilitates subsequent processing of the object name (Klatzky, Pellegrino, McKloskey, & Doherty, 1989). In Klatzky et al.'s study, participants learned to make specific hand shapes such as a pinch in response to icons. These icons were then presented as primes, followed by target sentences (e.g., *Insert a coin*) to which participants made sensibility judgments. Performance was affected positively when the primed hand shape matched the shape that would be needed to interact with the object in the sentence. The reverse was shown by Masson, Bub, and Warren (2008; see also Van Elk, van Schie, & Bekkering, 2008), who found that processing of object and action names primed subsequent actions for which the matching hand shape was needed. Similar findings have shown facilitation due to a match between the direction of a movement implied by a sentence and the actual movement needed to make a response, the action-compatibility effect (Borghi et al., 2004; Glenberg & Kaschak, 2002;

Scorolli, Borghi, & Glenberg, 2009; Taylor, Lev-Ari, & Zwaan, 2008). Glenberg and Kaschak showed that when participants made sensibility judgments to sentences describing actions toward the body (e.g., *Open the drawer*), they were faster if the response required them to move their hand toward themselves than if it required them to move their hand away from their body. The opposite was found when the sentence described an action away from the body (e.g., *Close the drawer*). These and similar findings strongly suggest that the motor system is involved in representing categories.

Sensory-Motor Systems Are Directly Involved in Representation

The studies discussed so far investigated the role of sensory-motor systems for categories in paradigms in which the perceptual and conceptual information was meaningfully related. For example, in Klatzky et al.'s (1989) experiments, the grasp that was primed was related to the grasp that would be needed for the object mentioned in the sentence. In Stanfield and Zwaan's (2001) experiment, the object in the picture was the same as the object in the sentence. It could be argued that these results show that sensory-motor information plays a role, but the locus of the effect might still be at some higher, more abstract semantic level rather than at the level of the sensory-motor systems. Therefore, we need to look at studies that have used paradigms in which a perceptual task and a conceptual task without a meaningful relation were used. McCloskey, Klatzky, and Pellegrino (1992) showed that concurrent motor planning of an unrelated action interfered with the hand shape priming effect on sentence processing. Investigating the role of perception, Van Dantzig, Pecher, Zeelenberg, and Barsalou (2008) adjusted the modality-switch paradigm. Rather than conceptual trials, they used a perceptual task (detection of meaningless visual, auditory, and tactile stimuli) as the context for conceptual property verification trials. They observed a modality-switch effect between the perceptual and conceptual trials. In particular, they observed a cost when the modality of the perceptual trial was different from that of the feature in the conceptual trial, paralleling the findings in the conceptual-only studies (Marques, 2006; Pecher et al., 2003). In contrast, Vermeulen, Corneille, and Niedenthal (2008) found that a concurrent perceptual memory load (meaningless visual shapes or auditory signals) interfered more with conceptual property verification trials if the property was from the same than from a different modality. Other studies have also shown that concurrent perceptual processing can interfere rather than facilitate conceptual processing. For example, Kaschak and colleagues (Kaschak et al., 2005, Kaschak, Zwaan, Aveyard, & Yaxley, 2006) showed that perceiving visual or auditory stimuli that depicted motion in a particular direction interfered with concurrent sentence comprehension if the sentence described an object moving in the same rather than different direction.

These studies suggest that whether overlap in perceptual and conceptual processing facilitates or harms performance depends on whether the tasks are performed at the same time or alternating. When the tasks are performed at the same time, they compete for resources, so greater overlap increases competition. When they alternate, there is no competition, and overlap may cause priming, for example, by focusing attention on the relevant modality. This picture is complicated, however, by studies that showed interference in an alternating paradigm. When participants processed linguistic stimuli in which a verb (e.g., *climb*; Richardson, Spivey, Barsalou, & McRae, 2003) or noun (e.g., *hat*; Estes, Verges, & Barsalou, 2008; Pecher, Van Dantzig, Boot, Zanolie, & Huber, 2010) pointed to a particular spatial location (e.g., *up* or *down*), their identification of a subsequently presented visual target (e.g., X or O) was harmed if the location of the visual target matched the implied location of the verb or noun. A possible explanation for these different findings is that in the studies by Richardson et al. and Estes et al. the perceptual representation of the conceptual stimulus was much richer than the simple perceptual stimuli used by Van Dantzig et al. The richer representation may have caused interference and may explain the differences in results.

Flexibility of Representations

An important issue is whether category representations should be considered in isolation or in context. In daily life, people seldom encounter categories in isolation. We never interact with just an apple in some empty space. Categories are usually embedded in a context; for example, we have an apple with our lunch in the cafeteria, or we pick an apple from a crate at the supermarket. Several studies have shown that context affects which features of categories are activated. In the previous sections I already discussed some studies that showed such an effect. For example, the studies on modality switching (Pecher et al., 2003) suggest that the activation of features from certain modalities is determined by the modality of a previous trial. Zwaan and colleagues showed that linguistic context affects the visual features of categories (e.g., whether a bird is represented with its wings stretched or folded). Another interesting finding is that goals (e.g., such as defined by the experimental task) affect which sensory-motor features are used for performance. Bub, Masson, and Bukach (2003; see also Bub, Masson, & Cree, 2008) showed that action-related information is activated only when the task required participants to perform those actions (e.g., grasp). Iachini, Borghi, and Senese (2008) showed that when participants made similarity judgments, shape was the most relevant feature, but when they sorted objects into categories, type of grip was the most relevant feature. Thus, various types of contexts affect categorical representations in different ways.

Further evidence for the flexibility of representations is provided by studies that show effects of prior context. Pecher et al. (1998) found priming for words that referred to objects with similar shapes (e.g., *banjo-tennis racket*), even though such information was irrelevant for the current task (lexical decision and word naming) as long as shape information had been activated in an earlier task. They argued that activation of the visual features in the prior task had made those features still more available later in the experiment (Barsalou, 1993), possibly due to altered representations (Goldstone, Lippa, & Shiffrin, 2001). Also using only words as stimuli, Pecher, Zeelenberg, and Barsalou (2004) extended these findings to other modalities in a property verification task. Even though initial processing was on word stimuli, further studies showed that the perceptual features that were made more available affected picture recognition (Pecher et al., 2009; Pecher, Zanolie, & Zeelenberg, 2007). For example, Pecher et al. (2007) presented object names (e.g., *chocolate*) with visual (e.g., *brown*) or nonvisual (e.g., *sweet*) property names in a property verification task. Later in the experiment, recognition of object pictures (e.g., a black-and-white drawing of a chocolate bar) was better for objects that had been presented with visual properties than with nonvisual properties, even though the particular visual property itself was not present in the picture. These findings suggest that during property verification participants simulated a visual representation of the object in order to verify the property. During this simulation, not only the relevant feature was activated but also other visual features such as shape. During the later recognition test the previously activated features were still more available. If the property was nonvisual, the simulation included no or fewer visual features. This flexibility of representations along modalities suggests that category representations are organized by sensory-motor modalities and that features can be strengthened selectively.

Perceptual Simulation in the Brain

Activation of Sensory-Motor Systems

The similarity between sensory-motor processing and category representation implies that they are supported by the same brain structures. Several studies have used functional neuroimaging techniques to identify activity in the brain while participants process categories. Chao and Martin (1999) presented colored and grayscale pictures and asked participants to passively view the pictures, name the objects, or name the color of objects. By contrasting passive viewing of colored and grayscale pictures, the areas involved in perception of color could be identified. By contrasting object naming and color naming for grayscale pictures, the areas involved in retrieving color knowledge could be identified. Retrieving color knowledge was associated with a wide network of activity. Of particular interest were occipital areas that were activated during color knowledge retrieval; these areas were adjacent rather than overlapping with color perception. In contrast, Simmons et al. (2007) found overlap in left fusiform gyrus between an active color perception task and color name retrieval for objects. They argued that it is important to compare brain activation for perception and representation within subjects and in both domains use tasks that require active processing.

Brain regions associated with processing of other modalities have also been shown to be more activated during processing of categories. Simmons, Martin, and Barsalou (2005) showed that while participants performed a memory task with pictures of foods there was increased activation of circuits associated with taste and reward processing. While Simmons et al. used pictures of foods, Goldberg, Perfetti, and Schneider (2006) showed that even when words were presented brain regions associated with visual, auditory, gustatory, and tactile processing were activated. They asked participants to verify properties from these modalities for objects, and they showed increased activations in the corresponding regions. Hauk, Johnsrude, and Pulvermüller (2004) obtained evidence that the activation of motor and premotor areas was organized somatotopically, such that words referring to actions with specific body parts (e.g., kick) were associated with activations in the corresponding region (e.g., the leg area). The involvement of different sensory-motor systems suggests that categories are supported by a widely distributed network of activation (Barsalou, 2008; Cree & McRae, 2003; Martin, 2007).

Domain-Specific Deficits

This view of categories as distributed patterns of activation may seem to be in contradiction with reports of patients who have category-specific deficits. A number of cases have been reported in the literature of patients with temporal lobe damage who show selective loss of knowledge for items from specific categories (Caramazza & Shelton, 1998; Warrington & Shallice, 1984). In the majority of cases these patients have lost knowledge of living things compared to nonliving things, although the opposite has also been reported. This double dissociation has led Caramazza and Shelton to argue for specialized mechanisms for living and nonliving things. They argued that conceptual knowledge is organized categorically in the brain. Such a categorical division would have evolved from evolutionary pressure to act with fast flight or feeding responses to certain animals and plants. As these specialized structures are selectively impaired, category-specific knowledge loss results.

Farah and McClelland (1991; see also Humphreys & Forde, 2001) demonstrated, however, that category-specific deficits can emerge from an architecture that has no separate structures for different categories. In their model, illustrated in Figure 24.1, categorical knowledge was distributed over patterns of units that represent functional and sensory features. These units were fully interconnected and activation was updated in parallel. They assumed that the proportions of sensory and functional features differed between living and nonliving things. Living things (e.g., *zebra*) are distinguished primarily by sensory features, whereas nonliving things (e.g., *hammer*) are distinguished primarily by functional features. For example, knowledge of most animals consists of what they look like and what sounds they make. Knowledge of tools, on the other hand, consists more of what they are used for. Farah and McClelland implemented this distinction in their model. They demonstrated that when the visual units were damaged, the model was impaired more for living than nonliving things, and when

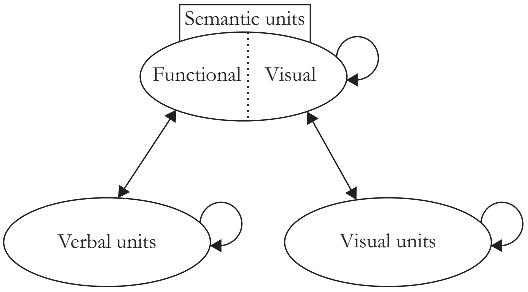

Figure 24.1 Farah and McClelland's (1991) model. The model has 24 verbal units, 24 picture units, 60 visual semantic units, and 20 functional semantic units. In the basic model, 20 living things were represented with 16.1 visual units and 2.1 functional units on average; 20 nonliving things were represented with 9.4 visual units and 6.7 functional units on average.

the functional units were damaged, the model was impaired more for nonliving than living things.

The distinction in impairments is not just between living and nonliving, however, because some categories (animals, fruits, vegetables, human-made foods, gems, and musical instruments) can be impaired separately or with the opposite domain (Cree & McRae, 2003). Cree and McRae (see also McRae & Cree, 2002) used feature production norms (McRae et al., 1997; McRae, Cree, Seidenberg, & McNorgan, 2005) to investigate the actual distribution of features from different knowledge types. The norms were collected by asking participants to list features for a total of 541 concepts from about 35 categories. For example, for the concept *pumpkin*, participants would produce properties such as *is round*, *is orange*, *has seeds*, *grows on vines*, *is eaten in pies*, and so on. Cree and McRae used the Wu and Barsalou (2009) knowledge type taxonomy to classify these responses into classes that correspond to sensory modalities, emotion, function, and more abstract features such as taxonomic knowledge. They showed that the pattern of impairments found in patients was best explained by a combination of differences in distribution over knowledge types between categories, differences in the number of distinguishing features, and concept familiarity. The most important finding was that categories differed greatly in the distribution of features over different modalities. For example, fruits and vegetables had a much higher number of color and taste features than creatures and nonliving things, and a much lower number of visual motion features than creatures. On the other hand, fruits and vegetables are similar to nonliving things because they are high on functional features and low on visual motion features. The distribution of features over knowledge types for different categories allowed Cree and McRae to explain many of the patterns of impairment. They hypothesized that knowledge types correspond to different brain regions, and that damage to a particular region would impair some categories more than others. Support for this idea is provided by Gainotti (2000), who reviewed a large number of case studies. Patients who show category-specific deficits differ widely in the locus of their lesions. According to Gainotti, these different patterns of damage and the resulting deficits show that categorical knowledge is supported by a network of brain areas that represent sensory-motor information.

In addition, Cree and McRae also showed that categories with more distinguishing features are less susceptible to damage than categories with fewer distinguishing features. Distinguishing features allow discrimination between concepts. For example, *has a trunk* distinguishes *elephants* from other animals, whereas *has ears* does not distinguish animals from each other. If features are lost, categories with fewer distinguishing features are more likely to be damaged than categories with more distinguishing features because the information that allows discrimination from other categories is no longer available. This finding also shows that a distributed explanation is more likely than a domain-specific explanation.

The models discussed so far assumed that categories are represented by patterns of activation in different brain regions that correspond to sensory modalities. A slightly different approach was taken by Plaut (2002). He also developed a distributed connectionist model of semantic knowledge, illustrated in Figure 24.2. In addition to different sets of units that represented visual, tactile, action, and phonological information, a set of hidden units formed the semantic knowledge representations. The architecture was such that the set of hidden units formed a sort of hub between the specialized units. The specialized units were connected only to other units within the same set and to the hidden semantic units. In this way the semantic units mediated between different modalities.

The model was trained to perform in two ways. First, it was trained to generate a name when given visual or tactile object input. Second, it was trained

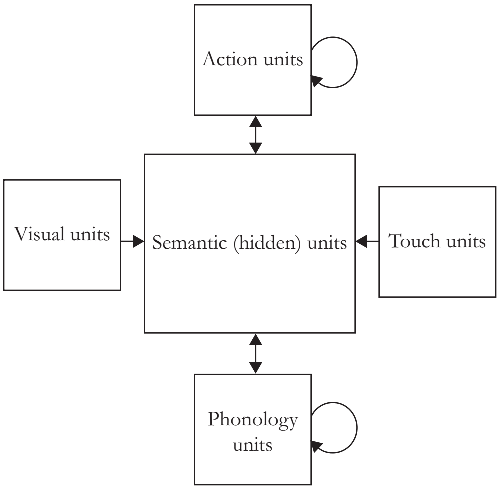

Figure 24.2 Plaut's (2002) model. The visual and touch units are input units, and each has 20 units. The action and phonology units are output units and also have 20 units each. There are 225 semantic units. The model represented 100 concepts, 20 exemplars each from five categories.

to generate both the name and an action when given visual or tactile input. The result of training was that the semantic units showed both categorical and modality-specific organization. Representations generated within the same modality had higher similarity than representations generated cross-modally. However, cross-modal representations of the same object were also highly similar. In fact, activation levels in the semantic units were not affected by modality, but the connection weights between semantic units and specialized units showed topographic organization. Semantic units near the specialized units had larger weights on input connections from that modality.

Other models also have hidden units that act as a hub. Using verbal descriptions of objects and visual features present in people's drawings of the same objects as input, Rogers et al. (2004) trained a connectionist model to represent objects in a layer of hidden "semantic" units. Their model is illustrated in Figure 24.3. Damage to these semantic units resulted in similar deficits as those observed in patients with semantic dementia, including failures to retrieve or use visual or verbal information. The deficits of the model across a wide variety of tasks could be explained by the similarity structure in the semantic units. As object representations were more similar, damage to the connection weights in the model caused them to drift, resulting in increasing difficulty to distinguish between similar representations. Thus, although the objects' similarities were expressed in the verbal or visual descriptions, the semantic units were sensitive to these similarities as well. However, Rogers et al. argued that the stability of the model's semantic representation still relied on the connectivity between the hidden units and the perceptual and verbal input units. Damage to the connections between visual and semantic units could cause deficits in a variety of tasks, including tasks in which no visual information is involved.

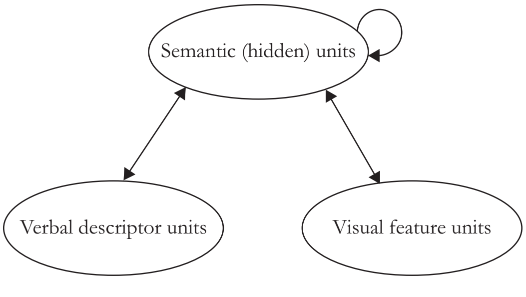

Figure 24.3 Rogers et al.'s (2004) model. The verbal descriptor units consisted of 40 name units, 64 perceptual units, 32 functional units, and 16 encyclopedic units. In addition, there were 64 visual feature units and 64 semantic units. Inputs were verbal features from production norms and descriptions of drawings for 62 objects.

An important question is to what extent such hidden units truly represent semantic knowledge or whether they only mediate between different kinds of knowledge of objects. Rogers et al. (2004) stated that their model captures the similarities between objects across domains in an abstract form. However, their semantic units do not explicitly encode information but should be viewed as links between visual and verbal representations. As such, they should be considered semantic in the function they perform and not in their content. Given an input pattern at one of the sets of input units (visual, verbal, or name), the model settled into a stable state that included patterns at the other input units. As an example, one of the tasks that the model was made to perform was naming from visual input. To simulate presenting a picture, a pattern of activation was presented at the visual input units. Because there were no direct connections between visual and name units, updating had to happen via the hidden semantic units. Once the name units were in a stable state, the object name was produced. Thus, the semantic units encoded neither visual nor verbal information but allowed updating of the name units by mediating between visual and verbal units. Thus, the semantic units form a convergence zone (Damasio, Grabowski, Tranel, Hichwa, & Damasio, 1996) or a semantic hub (Patterson, Nestor, & Rogers, 2007; see also Kellenbach, Brett, & Patterson, 2001).

Another type of model does not assume a separation between different types of input modalities but rather has one single layer of semantic units. McRae et al. (1997) used feature production norms to train their model, which consisted of a layer of word-form units and a layer of semantic units, as illustrated in Figure 24.4. This model was able to explain various results from speeded semantic tasks with healthy subjects. An important finding was that variability in the degree of feature intercorrelations can explain differences between categories. Artifacts have fewer intercorrelated features than natural kinds. McRae et al. showed that priming effects for artifacts were predicted better by overlap in individual features, whereas priming effects for natural kinds were predicted better by overlap in intercorrelated features. Devlin, Gonnerman, Andersen, and Seidenberg (1998; see also Tyler, Moss, Durrant-Peatfield, & Levy, 2000) showed that a model in which such differences in intercorrelated features was preserved could account for the double dissociation observed

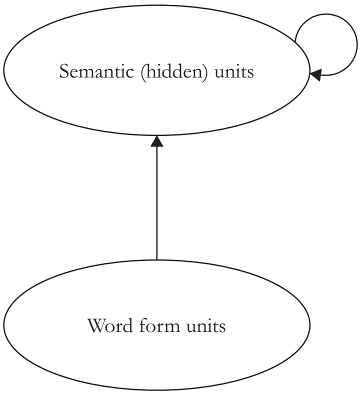

Figure 24.4 McRae et al.'s (1997) model. The model had 379 word-form units and 646 semantic units and represented 84 words. The representations were based on feature production norms.

in Alzheimer's patients. At low levels of damage, categories that had lots of intercorrelated features were less susceptible to nonfocal damage (as is typically found with Alzheimer's patients), because the strong intercorrelations allowed pattern completion even for weaker features. However, as damage got more severe, entire sets of intercorrelated features were lost, resulting in impairment of entire superordinate categories. Devlin et al.'s simulations showed that the pattern of deficits paralleled those found for patients. When only small proportions of semantic connections were damaged, there was, on average, a small artifact deficit. With more damage, however, there was a larger deficit of natural kinds. The simulations also showed large variability in patterns, consistent with the variability found between patients.

The distributed nature of these models seems to be at odds with functional magnetic resonance imaging (fMRI) data that show specialized areas for certain categories of objects such as faces and houses (Haxby et al., 2001). This may be due to the sort of subtraction techniques often used with fMRI research. In typical studies, participants process two types of stimuli (e.g., faces vs. tools), and the areas that show significantly more BOLD activation for one category than the other are appointed the role of specialized processor of that category. Such techniques ignore the role of areas that are involved in more than one category because these get subtracted out.

Although most fMRI research thus focuses on finding localized areas for categories, it is possible to investigate the kind of distributed representations as are assumed by the models described earlier. Haxby et al. (2001) used an analysis technique that was aimed at distributed patterns of activation across large parts of the cortex. They presented pictures of different exemplars from seven categories and examined the patterns of voxel activation in the ventral temporal cortex. For each category, correlations between different runs of the same category were higher than correlations between runs of different categories. More important, even if the voxels that responded maximally to that particular category were removed, the remaining pattern was still more similar to other same category patterns than to different category patterns. Thus, these data indicate that categories are represented by a distributed pattern of activation rather than specialized areas.

The Role of Language

Language Binds Experiences

Building on earlier proposals (Glaser, 1992; Pavio, 1986), Simmons, Hamann, Harenski, Hu, and Barsalou (2008; see also Louwerse & Jeuniaux, 2008) argued that conceptual processing is a mixture of superficial linguistic processing and deeper, sensory-motor simulations. Using fMRI, Simmons et al. showed that a conceptual task (property generation) shared patterns of brain activation with both word association and situation generation. Moreover, they argued that the activation associated with linguistic processing peaked earlier than the activations associated with sensory-motor simulations. They proposed that conceptual processing is supported by two parallel streams of activation. The faster stream is based on the linguistic system and reflects associations between words. The slower stream is based on sensory-motor systems and reflects situated simulations of concepts. Differences in task requirements cause differences in recruitment of these two streams. Tasks that can be performed at a superficial level rely mostly on the linguistic system, whereas tasks that require deeper conceptual processing rely more on sensory-motor systems. Solomon and Barsalou (2004) demonstrated that the effect of perceptual variables in a property verification task was modulated by the extent to which the task could be performed by word association. In their task, participants had to verify whether the property was a part of the concept (e.g., *cat-ear*). Solomon and Barsalou manipulated whether the false trials contained associated concept-property pairs (e.g., *owl-tree*). When only the true trials were associated, participants could use superficial processing based on word associations. When both true and false trials were associated, however, participants had to use deeper processing, and in that case perceptual variables affected their performance.

Although some people may think of linguistic processing and simulation as two separate routes, it is much more likely that these types of processing interact and share processing mechanisms. A possible mechanism for the interaction between linguistic processing and simulation is the idea of a convergence zone (Damasio et al., 1996) or semantic hub (Patterson et al., 2007). Linguistic information and sensory-motor information from different modalities are represented in modality-specific systems, and they are linked through central areas whose function is to link information from these different modalities together. With such a mechanism, object identities are formed and linked to names. For example, the word *apple* will be linked to a shape representation on one occasion, while on another occasion the word *apple* will be linked to a taste representation. Models such as those developed by Plaut (2002) and Rogers et al. (2004) show that the resulting representations in semantic hubs (the hidden layers in their models) are organized according to semantic similarity. It is important to note that these representations do not contain any meaning. The hub does not represent the color or taste of an apple; it only allows this information to be activated in the specialized sensory areas when, for example, the word *apple* is presented. However, because the hub has a semantic organization, activation of a pattern in the hub could lead to activation of related words without the need to activate the word's meaning. Therefore, it is possible that for superficial processing the links between the language area and the hub are sufficient.

The role of language might be to connect different sensory-motor experiences to the same category. In this way, category identities may develop even when experiences do not share features. For example, the experience of drinking apple juice and the experience of picking up an apple in a shop have little in common. By using the same category name (*apple)* for both experiences, they become connected and form rich representations.

Andrews, Vigliocco, and Vinson (2009) argue that both types of input are important. In their model, sensory-motor information and language information are treated as a single combined data set. They used feature production norms as a proxy for sensory-motor experiences, and word co-occurrences as linguistic input. The word co-occurrence data were based on an approach similar to LSA (Landauer & Dumais, 1997). In LSA, text is used as input, and the model computes how often words occur in particular texts. Based on a large corpus of texts, words are represented as vectors of co-occurrence frequencies in the texts. Landauer and Dumais showed that words that occur in similar sets of texts have similar vectors and can be viewed as nearby points in a multidimensional co-occurrence space. Distances in this space tend to be highly correlated to semantic similarity. Andrews et al. argued that a probabilistic model that was trained using the linguistic and sensory-motor data concurrently was a better predictor of human performance than models based on either source of data alone or based on using the two sources independently.

Thus, instead of language and sensory-motor representations as being separate, parallel processes, they are part of the same network. Language binds different sensory-motor experiences to form coherent categories. During language processing, meaning is represented by activation of a pattern across sensory-motor systems. However, in tasks in which performance can be based on word associations, activation of other words via the semantic hub might be sufficient. The advantage of such shortcuts is that the system does not need to wait for full activation of representations in the sensory-motor system. To represent meaning fully, however, these representations are necessary.

Abstract Concepts

An interesting aspect of the Andrews et al. (2009) model is that it can infer features for concepts for which no sensory-motor input was available. This might provide a solution to the problem of how abstract categories are represented (Barsalou, 1999; Barsalou & Wiemer-Hastings, 2005; Dove, 2009; Prinz, 2002). Since abstract categories (e.g., *democracy*, *respect*) have no perceptual features, explaining how they can be grounded in sensory-motor representations provides a challenge. Andrews et al. attempted to solve this problem by attributing features from words that have similar word co-occurrence vectors. However, from the examples that they provided, it is not immediately obvious that the resulting features are perceptual. For example, the features that are produced (by the model) for the abstract word *obsession* are *women*, *scream*, *crave*, *desire*, *relieve*, *love*, *discomfort*, *burn*, *explode*, and *attack*. Rather than describing perceptual experiences, some of these words are abstract themselves, and of those that do describe perceivable features, some seem only indirect aspects of the experience of *obsession* (e.g., *burn*, *explode*, *attack*). The question is, of course, what sensory-motor experiences would represent such concepts.

Several other ideas for how abstract concepts might be grounded have been proposed (e.g., Barsalou, 1999, Barsalou & Wiemer-Hastings, 2005; Prinz, 2002). At present, the most popular theory is that people use metaphors and image schemata to ground abstract concepts in bodily experiences. For example, people may understand the process of solving a problem in terms of travelling from a starting point (the problem situation) to a destination (the solution) along a path (the method that is used to solve the problem), as is illustrated by expressions such as *to get sidetracked* or *to have something get in one's way* (Gibbs, 1994, 2005; Lakoff, 1987; Lakoff & Johnson, 1980; but see Barsalou & Wiemer-Hastings, 2005; Murphy, 1996). Thus, the concrete situation of travelling along a path is used as a metaphor for an abstract situation such as solving a problem. Because the metaphor refers to a concrete physical experience, embodied theories can explain how the abstract concept is grounded in the perceptual and motor systems.

Whereas most of the evidence given in support of this theory comes from cognitive linguistics, recent studies have provided some evidence that image schemata are activated by abstract concepts (Boot & Pecher, 2010, 2011; Boroditsky & Ramscar, 2002; Richardson et al., 2003; Spivey, Richardson, & Gonzalez-Marquez, 2005; Zanolie, Van Dantzig, Boot, Wijnen, Schubert, Giessner, & Pecher, 2012; see Pecher, Boot, & Van Dantzig, 2011, for an extended discussion). The question is to what extent these results are proof of grounded representations. Although image schemata refer to basic bodily experiences, they do so in quite an abstract way. For example, several concepts might be represented with the verticality image schema, such as *power*, *valence*, *status*, and so on. However, the concept of *power* must be much richer than just the verticality image schema. Image schemata may represent some features of abstract concepts, but the full representation needs additional features.

A second proposal for grounding abstract concepts is by simulations of introspective experiences (Barsalou, 1999; Barsalou & Wiemer-Hastings, 2005). For example, introspective experiences may be associated with being hungry, feeling happy, or having a goal. People can perceive their internal states and can simulate internal states to represent concepts. Introspection could be considered another sensory modality. Just as for sensory modalities, people can switch attention from introspection to other modalities such as visual perception (Oosterwijk et al., 2009). Barsalou and Wiemer-Hastings found a greater focus on introspective properties for abstract than for concrete concepts. The idea of introspection needs further investigation, however. While it may be more or less clear how people perceive that they are hungry or aroused, it is less obvious how people know that they have goals or beliefs, or that they are trying to retrieve something from memory, without postulating a homunculus. Possibly, introspective experiences can be part of a representation as grounded features, but they do not provide the full meaning of a concept.

A third proposal is that abstract concepts are represented by concrete situations (Barsalou & Wiemer-Hastings, 2005). Likely, a collection of concrete situations that share the abstract concept combine to form a rich representation. This proposal has similarities to exemplar models of categorization (Hintzman, 1986; Nosofsky, 1988). In exemplar models, each encounter with an exemplar is stored. Abstraction across exemplars is achieved when a cue activates several different exemplars. These are then combined as a response to the cue (e.g., as a combined similarity measure or as a summary representation) in order to be used for processing. Representation by concrete situations allows these representations to be grounded in sensory-motor simulations. For example, the concept *democracy* may be represented by *a meeting of parliament*, *a succession of speeches*, *votes on proposals during meetings*, *election campaigns*, *a voter deciding on her vote*, *going into a booth with a ballot*, *availability of multiple views in the media*, and so on. Barsalou and Wiemer-Hastings found that situations were important aspects for all types of concepts, constituting about half of all produced properties, but even more for abstract than concrete concepts. Thus, this idea has great promise. So far, however, it is still in its early stages of development.

General Discussion

Is Sensory-Motor Simulation Necessary?

In this chapter I have set out to describe the role of sensory-motor simulations for mental categories. The evidence from behavioral studies, brain imaging, patient studies, and models of category representation are consistent with the idea that sensory-motor systems support representation by a simulation mechanism. An important question, however, is whether these sensory-motor simulations are necessary for representation. Theories of grounded cognition propose that they are, because the core assumption of such theories is that a simulation and a concept are the same thing. For example, Glenberg (1997) proposes that concepts are potential action patterns. Thus, in this view, there are no amodal symbols that represent a concept. Mahon and Caramazza (2008), on the other hand, have argued that much of the evidence is also consistent with a system in which representation is initially separate from sensory-motor systems, and in which activation cascades to those systems only *after* a category has been represented by amodal symbols, or in which activation spreads in parallel to amodal and sensory-motor systems, but the sensory-motor activation is not fundamental to the category representation. Thus, studies that show activation of sensory-motor systems in the brain while participants perform a representational task (e.g., read language) do not necessarily show that such activation supports representation. The activation of sensory-motor systems might merely be a side effect of representing categories. The same explanation might be applied to behavioral studies that show activation of sensory-motor information during representation.

It is more difficult (but perhaps not impossible) for such a coactivation account to explain data that show an effect of perceptual variables that precede representation. For example, studies show deficits in performance when sensory-motor systems are damaged or occupied by other tasks. Although some models have shown that domain-specific deficits are predicted by models that assume a single semantic system (Devlin et al., 1998; McRae et al., 1997), more detailed studies showed that deficits are most likely due to damage to processing areas for specific sensory-motor information (Cree & McRae, 2003; Gainotti, 2000). Healthy participants also showed deteriorated performance in a verbal property verification task when the property was from the same modality as a concurrently performed perceptual task (Vermeulen et al., 2008). The fact that representation is more difficult when the specific sensory system has fewer resources strongly suggests that these systems perform an essential role. Using a slightly different paradigm, Van Dantzig et al. (2008) showed facilitation for verbal property verification if a previous perceptual stimulus was from the same modality. Again, this is hard to reconcile with an explanation that assumes mere coactivation of sensory information. Although it remains possible that some aspects of representation are more symbolic, at least an important part has to be supported by sensory-motor systems in order to explain these findings.

Is Simulation Task-Induced Imagery?

An important question is to what extent the evidence presented so far reflects automatic representation. In laboratory experiments participants may develop strategies in order to cope with a task. In cases where sensory-motor variables affect conceptual processing, one may wonder whether conscious imagery rather than automatic representational processing can explain such effects. Thus, much of the work on the role of sensory-motor systems for category representations may suggest that representation is a form of imagery. As with categories, there is evidence that mental imagery shares modality-specific mechanisms at behavioral (Rouw, Kosslyn, & Hamel, 1997) and neurological levels (Borst & Kosslyn, 2008). On the other hand, important differences exist between imagery and categorical representations (Barsalou, 1999, 2009). First, there is a difference in conscious control. Imagery tasks require effortful processes such as rotating or reorganizing mental images, whereas the representation of a category may take place without conscious awareness or control. Second, imagery ability varies widely between individuals (Blajenkova, Kozhevnikov, & Motes, 2006; Burton & Fogarty, 2003; Kosslyn, Brunn, Cave, & Wallach, 1984), whereas representing conceptual knowledge is performed easily by anyone with normal cognitive abilities. Several studies have shown that perceptual effects in representation do not vary with imagery ability or preference (Pecher, Van Dantzig, & Schifferstein, 2009; Stanfield & Zwaan, 2001), suggesting that the involvement of sensory-motor systems for representation is automatic.

Conclusion

Mental categories are (at least for a part) supported by sensory-motor simulations. There is a wealth of evidence showing that mental categories retain the sensory-motor qualities of their physical counterparts, such as modality-specific features. These simulations are highly flexible, and just as in sensory-motor interactions, they can focus on specific modalities, change according to context, take perspective into account, and so on. Although simulations are temporary processes that represent categories during online processing, they can have longer lasting impacts. Several studies have shown that when concepts are repeated, later representations are affected by earlier ones as if they had been interacted with physically. Several findings of interactions between representation and perception and the activation of similar brain areas for representation and perception all point to the conclusion that they are supported by the same processing mechanisms.

Future Directions

Although the aforementioned conclusion is supported by a lot of research, there are some important remaining questions. First of all, as was already discussed earlier, more research is needed to show how fundamental the role of sensory-motor mechanisms is for representations. Are simulations essential for representation, do they support representation only partly, or are they merely by-products of otherwise symbolic operations? As some connectionist frameworks show, representations might be widely distributed, which complicates the question of what is essential and what is a by-product. In such models, all kinds of information interact and support each other. Thus, even if there are more abstract, symbolic aspects to representation, they might still be affected by manipulations that tap into sensory-motor processes. Therefore, the distinction between grounded and nongrounded theories may turn out to be artificial.

A second, very important question is how sensory-motor simulations can represent abstract concepts. Research supporting the grounded cognition framework so far has mainly found evidence for representations of concrete things such as *apples* and *eagles*. It can be argued, however, that most of our representations and other cognitive operations concern abstract things such as *democracy* or *regret*. Several mechanisms have been proposed, and of these, the conceptual metaphor theory has received most attention. It is unlikely, however, that this theory can fully explain abstract concepts, because these concepts are much richer than simple image schemata. Other ideas are still in too early stages to allow evaluation. It is crucial that this question gets resolved, because a theory that can deal only with concrete concepts is too limited.

A more methodological challenge is how we can measure what people's sensory-motor experiences are. Most researchers have used their own (informed) intuitions when manipulating sensory-motor features of representations. Some have been more thorough and collected norms (e.g., McRae et al., 2005). Still, often the kinds of features that are used are those that can be described by words. One may wonder whether words can accurately describe sensory-motor experiences. Take, for example, colors. The color red may be used for various things (hair, wine, earth, fire truck) that are all red but in very different ways. For other modalities it is often even harder to accurately describe sensory experiences. For example, there are hardly any words that describe smells except for names of other things that have that smell, hence the interesting vocabulary of wine tasters. Even if there are words to describe an experience, one may wonder whether this is the right grain size for perceptual symbols.

Finally, as some research has shown, concepts are affected by context. As things in the world are not experienced in isolation, it seems likely that concepts are also not represented in isolation. The framework I have discussed in this chapter views representations as simulations of experiences. It seems likely, therefore, that such a framework is especially suited to take context into account.

References

Andrews, M., Vigliocco, G., & Vinson, D. (2009). Integrating experiential and distributional data to learn semantic representations. *Psychological Review*, *116*, 463–498.

Barsalou, L. W. (1990). On the indistinguishability of exemplar memory and abstraction in category representation. In T. K. Srull & R. S. Wyer (Eds.), *Advances in social cognition, volume III: Content and process specificity in the effects of prior experiences* (pp. 61–88). Hillsdale, NJ: Lawrence Erlbaum Associates.

Barsalou, L. W. (1993). Flexibility, structure, and linguistic vagary in concepts: Manifestations of a compositional system of perceptual symbols. In A. F. Collins , S. E. Gathercole , M. A. Conway, & P. E. Morris (Eds.), *Theories of memory* (pp. 29–101). Hove, England: Erlbaum.

Barsalou, L. W. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences*, *22*, 577–660.

Barsalou, L. W. (2008). Grounding symbolic operations in the brain's modal systems. In G. R. Semin & E. R. Smith (Eds.), *Embodied grounding: Social, cognitive, affective, and neuroscientific approaches* (pp. 9–42). New York: Cambridge University Press.

Barsalou, L. W. (2009). Simulation, situated conceptualization, and prediction. *Philosophical Transactions of the Royal Society B*, *364*, 1281–1289.

Barsalou, L. W., Simmons, W. K., Barbey, A. K., & Wilson, C. D. (2003). Grounding conceptual knowledge in modality-specific systems. *Trends in Cognitive Sciences*, *7*, 84–91.

Barsalou, L. W., & Wiemer-Hastings, K. (2005). Situating abstract concepts. In D. Pecher & R. A. Zwaan (Eds.), *Grounding cognition: The role of perception and action in memory, language, and thinking* (pp. 129–163). Cambridge, England: Cambridge University Press.

Blajenkova, O., Kozhevnikov, M., & Motes, M. A. (2006). Object-spatial imagery: A new self-report imagery questionnaire. *Applied Cognitive Psychology*, *20*, 239–263.

Boot, I., & Pecher, D. (2010) Similarity is closeness: Metaphorical mapping in a perceptual task. *Quarterly Journal of Experimental Psychology*, *63*, 942–954.

Boot, I., &Pecher, D. (2011). Representation of categories: Metaphorical use of the container schema. *Experimental Psychology, 58, 162–170.*

Borghi, A. M., Glenberg, A. M., & Kaschak, M. P. (2004). Putting words in perspective. *Memory and Cognition*, *32*, 863–873.

Boroditsky, L., & Ramscar, M. (2002). The roles of body and mind in abstract thought. *Psychological Science*, *13*, 185–189.

Borst, G., & Kosslyn, S. M. (2008). Visual mental imagery and visual perception: Structural equivalence revealed by scanning processes. *Memory and Cognition*, *36*, 849–862.

Bub, D. N., Masson, M. E. J., & Bukach, C. M. (2003). Gesturing and naming: The use of functional knowledge in object identification. *Psychological Science*, *14*, 467–472.

Bub, D. N., Masson, M. E. J., & Cree, G. S. (2008). Evocation of functional and volumetric gestural knowledge by objects and words. *Cognition*, *106*, 27–58.

Burton, L. J., & Fogarty, G. J. (2003). The factor structure of visual imagery and spatial abilities. *Intelligence*, *31*, 289–318.

Caramazza, A., & Shelton, J. R. (1998). Domain-specific knowledge systems in the brain: The animate-inanimate distinction. *Journal of Cognitive Neuroscience*, *10*, 1–34.

Chao, L. L., & Martin, A. (1999). Cortical regions associated with perceiving, naming, and knowing about colors. *Journal of Cognitive Neuroscience*, *11*, 25–35.

Connell, L. (2007). Representing object colour in language comprehension. *Cognition*, *102*, 476–485.

Cree, G. S., & Mc Rae, K. (2003). Analyzing the factors underlying the structure and computation of the meaning of chipmunk, cherry, chisel, cheese, and cello (and many other such concrete nouns). *Journal of Experimental Psychology: General*, *132*, 163–201.

Damasio, H., Grabowski, T. J., Tranel, D., Hichwa, R. D., & Damasio, A. R. (1996). A neural basis for lexical retrieval. *Nature*, *380*, 499–505.

Devlin, J. T., Gonnerman, L. M., Andersen, E. S., & Seidenberg, M. S. (1998). Category-specific semantic deficits in focal and widespread brain damage: A computational account. *Journal of Cognitive Neuroscience*, *10*, 77–94.

Dove, G. (2009). Beyond perceptual symbols: A call for representational pluralism. *Cognition*, *110*, 412–431.

Estes, Z., Verges, M., & Barsalou, L. W. (2008). Head up, foot down: Object words orient attention to the objects' typical location. *Psychological Science*, *19*, 93–97.

Farah, M. J., & Mc Clelland, J. L. (1991). A computational model of semantic memory impairment: Modality specificity and emergent category specificity. *Journal of Experimental Psychology: General*, *120*, 339–357.

Gainotti, G. (2000). What the locus of brain lesion tells us about the nature of the cognitive defect underlying category-specific disorders: A review. *Cortex*, *36*, 539–559.

Gibbs, R. W. J. (1994). *The poetics of mind: Figurative thought, language, and understanding*. New York: Cambridge University Press.

Gibbs, R. W. J. (2005). Embodiment in metaphorical imagination. In D. Pecher & R. A. Zwaan (Eds.), *Grounding cognition: The role of perception and action in memory, language, and thinking* (pp. 65–92). Cambridge, England: Cambridge University Press.

Glaser, W. R. (1992). Picture naming. *Cognition*, *42*, 61–105.

Glenberg, A. M. (1997). What memory is for. *Behavioral and Brain Sciences*, *20*, 1–55.

Glenberg, A. M., & Kaschak, M. P. (2002). Grounding language in action. *Psychonomic Bulletin and Review*, *9*, 558–565.

Goldberg, R. F., Perfetti, C. A., & Schneider, W. (2006). Perceptual knowledge retrieval activates sensory brain regions. *Journal of Neuroscience*, *26*, 4917–4921.

Goldstone, R. L., Lippa, Y., & Shiffrin, R. M. (2001). Altering object representations through category learning. *Cognition*, *78*, 27–43.

Hauk, O., Johnsrude, I., & Pulvermüller, F. (2004). Somatotopic representation of action words in human motor and premotor cortex. *Neuron*, *41*, 301–307.

Haxby, J. V., Gobbini, M. I., Furey, M. L., Ishai, A., Schouten, J. L., & Pietrini, P. (2001). Distributed and overlapping representations of faces and objects in ventral temporal cortex. *Science*, *293*, 2425–2430.

Hintzman, D. L. (1986). Schema abstraction in a multiple-trace memory model. *Psychological Review*, *93*, 411–428.

Humphreys, G. W., & Forde, E. M. E. (2001). Hierarchies, similarity, and interactivity in object recognition: "Category-specific" neuropsychological deficits. *Behavioral and Brain Sciences*, *24*, 453–509.

Iachini, T., Borghi, A. M., & Senese, V. P. (2008). Categorization and sensorimotor interaction with objects. *Brain and Cognition*, *67*, 31–43.

Kaschak, M. P., Madden, C. J., Therriault, D. J., Yaxley, R. H., Aveyard, M., Blanchard, A. A., & Zwaan, R. A. (2005). Perception of motion affects language processing. *Cognition*, *94*, B79–B89.

Kaschak, M. P., Zwaan, R. A., Aveyard, M., & Yaxley, R. H. (2006). Perception of auditory motion affects language processing. *Cognitive Science*, *30*, 733–744.

Kellenbach, M. L., Brett, M., & Patterson, K. (2001). Large, colorful, or noisy? Attribute- and modality-specific activations during retrieval of perceptual attribute knowledge. *Cognitive, Affective and Behavioral Neuroscience*, *1*, 207–221.

Klatzky, R. L., Pellegrino, J. W., Mc Closkey, B. P., & Doherty, S. (1989). Can you squeeze a tomato? The role of motor representations in semantic sensibility judgments. *Journal of Memory and Language*, *28*, 56–77.

Kosslyn, S. M., Brunn, J., Cave, K. R., & Wallach, R. W. (1984). Individual differences in mental imagery ability: A computational analysis. *Cognition*, *18*, 195–243.

Lakoff, G. (1987). *Women, fire, and dangerous things*. Chicago: Chicago University Press.

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

Landauer, T. K., & Dumais, S. T. (1997). A solution to Plato's problem: The latent semantic analysis theory of acquisition, induction, and representation of knowledge. *Psychological Review*, *104*, 211–240.

Louwerse, M. M., & Jeuniaux, P. (2008). Language comprehension is both embodied and symbolic. In M. De Vega , A. M. Glenberg, & A. C. Graesser (Eds.), *Embodiment and meaning: A debate* (pp. 309–326). Oxford, England: Oxford University Press.

Mahon, B. Z., & Caramazza, A. (2008). A critical look at the embodied cognition hypothesis and a new proposal for grounding conceptual content. *Journal of Physiology (Paris)*, *102*, 59–70.

Marques, J. F. (2006). Specialization and semantic organization: Evidence for multiple semantics linked to sensory modalities. *Memory and Cognition*, *34*, 60–67.

Martin, A. (2007). The representation of object concepts in the brain. *Annual Review of Psychology*, *58*, 25–45.

Masson, M. E. J. (1995). A distributed memory model of semantic priming. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *21*, 3–23.

Masson, M. E. J., Bub, D. N., & Warren, C. M. (2008). Kicking calculators: Contribution of embodied representations to sentence comprehension. *Journal of Memory and Language*, *59*, 256–265.

Mc Closkey, B. P., Klatzky, R. L., & Pellegrino, J. W. (1992). Rubbing your stomach while tapping your fingers: Interference between motor planning and semantic judgments. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 948–961.

McRae, K., & Cree, G. S. (2002). Factors underlying category-specific semantic deficits. In E. M. E. Forde & G. W. Humphreys (Eds.), *Category specificity in brain and mind* (pp. 211–249). Hove, England: Psychology Press.

McRae, K., Cree, G. S., Seidenberg, M. S., & McNorgan, C. (2005). Semantic feature production norms for a large set of living and nonliving things. *Behavior Research Methods*, *37*, 547–559.

McRae, K., Cree, G. S., Westmacott, R., & De Sa, V. R. (1999). Further evidence for feature correlations in semantic memory. *Canadian Journal of Experimental Psychology*, *53*, 360–373.

McRae, K., De Sa, V. R., & Seidenberg, M. S. (1997). On the nature and scope of featural representations of word meaning. *Journal of Experimental Psychology: General*, *126*, 99–130.

Murphy, G. L. (1996). On metaphoric representation. *Cognition*, *60*, 173–204.

Murphy, G. L. (2002). *The big book of concepts*. Cambridge: MIT Press.

Oosterwijk, S., Winkielman, P., Pecher, D., Zeelenberg, R., Rotteveel, M., & Fischer, A. H. (2012). Mental states inside out: Switching costs for emotional and nonemotional sentences that differ in internal and external focus. *Memory and Cognition, 40*, 93–100.

Nosofsky, R. M. (1988). Similarity, frequency, and category representations. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *14*, 54–65.

Patterson, K., Nestor, P. J., & Rogers, T. T. (2007). Where do you know what you know? The representation of semantic knowledge in the human brain. *Nature Reviews: Neuroscience*, *8*, 976–987.

Pavio, A. (1986). *Mental representations: A dual coding approach.* Oxford, England: Oxford University Press.

Pecher, D., Boot, I., & Van Dantzig, S. (2011). Abstract concepts: Sensory-motor grounding, metaphors, and beyond. In B. H. Ross (Ed.), *The psychology of learning and motivation* (pp. 217–248). Burlington: Academic Press.

Pecher, D., van Dantzig, S., Boot, I., Zanolie, K., & Huber, D. E. (2010). Congruency between word position and meaning is caused by task induced spatial attention. *Frontiers in Cognition*, *1,* 30.

Pecher, D., v an Dantzig, S., & Schifferstein, H. N. J. (2009). Concepts are not represented by imagery. *Psychonomic Bulletin and Review*, *16*, 914–919.

Pecher, D., van Dantzig, S., Zwaan, R. A., & Zeelenberg, R. (2009). Language comprehenders retain implied shape and orientation of objects. *Quarterly Journal of Experimental Psychology*, *62*, 1108–1114.

Pecher, D., Zanolie, K., & Zeelenberg, R. (2007). Verifying visual properties in sentence verification facilitates picture recognition memory. *Experimental Psychology*, *54*, 173–179.

Pecher, D., Zeelenberg, R., & Barsalou, L. W. (2003). Verifying different-modality properties for concepts produces switching costs. *Psychological Science*, *14*, 119–124.

Pecher, D., Zeelenberg, R., & Barsalou, L. W. (2004). Sensorimotor simulations underlie conceptual representations: Modality-specific effects of prior activation. *Psychonomic Bulletin and Review*, *11*, 164–167.

Pecher, D., Zeelenberg, R., & Raaijmakers, J. G. W. (1998). Does pizza prime coin? perceptual priming in lexical decision and pronunciation. *Journal of Memory and Language*, *38*, 401–418.

Plaut, D. C. (2002). Graded modality specific specialisation in semantics: A computational account of optic aphasia. *Cognitive Neuropsychology*, *19*, 603–639.

Prinz, J. J. (2002). *Furnishing the mind: Concepts and their perceptual basis*. Cambridge, MA: MIT Press.

Pulvermüller, F. (1999). Words in the brain's language. *Behavioral and Brain Sciences*, *22*, 253–336.

Richardson, D. C., Spivey, M. J., Barsalou, L. W., & McRae, K. (2003). Spatial representations activated during real-time comprehension of verbs. *Cognitive Science*, *27*, 767–780.

Rogers, T. T., Lambon Ralph, M. A., Garrard, P., Bozeat, S., McClelland, J. L., Hodges, J. R., & Patterson, K. (2004). Structure and deterioration of semantic memory: A neuropsychological and computational investigation. *Psychological Review*, *111*, 205–235.

Rouw, R., Kosslyn, S. M., & Hamel, R. (1997). Detecting high-level and low-level properties in visual images and visual percepts. *Cognition*, *63*, 209–226.

Scorolli, C., Borghi, A. M., & Glenberg, A. M. (2009). Language-induced motor activity in bi-manual object lifting. *Experimental Brain Research*, *193*, 43–53.

Simmons, W. K., Hamann, S. B., Harenski, C. L., Hu, X. P., & Barsalou, L. W. (2008). fMRI evidence for word association and situated simulation in conceptual processing. *Journal of Physiology Paris*, *102*, 106–119.

Simmons, W. K., Martin, A., & Barsalou, L. W. (2005). Pictures of appetizing foods activate gustatory cortices for taste and reward. *Cerebral Cortex*, *15*, 1602–1608.

Simmons, W. K., Ramjee, V., Beauchamp, M. S., McRae, K., Martin, A., & Barsalou, L. W. (2007). A common neural substrate for perceiving and knowing about color. *Neuropsychologia*, *45*, 2802–2810.

Solomon, K. O., & Barsalou, L. W. (2001). Representing properties locally. *Cognitive Psychology*, *43*, 129–169.

Solomon, K. O., & Barsalou, L. W. (2004). Perceptual simulation in property verification. *Memory and Cognition*, *32*, 244–259.

Spence, C., Nicholls, M. R., & Driver, J. (2001). The cost of expecting events in the wrong sensory modality. *Perception and Psychophysics*, *63*, 330–336.

Spivey, M. J., Richardson, D. C., & Gonzalez- Marquez, M. (2005). On the perceptual-motor and image-schematic infrastructure of language. In D. Pecher & R. A. Zwaan (Eds.), *Grounding cognition: The role of perception and action in memory, language, and thinking* (pp. 246–281). Cambridge, England: Cambridge University Press.

Stanfield, R. A., & Zwaan, R. A. (2001). The effect of implied orientation derived from verbal context on picture recognition. *Psychological Science*, *12*, 153–156.

Taylor, L. J., Lev-Ari, S., & Zwaan, R. A. (2008). Inferences about action engage action systems. *Brain and Language*, *107*, 62–67.

Tyler, L. K., Moss, H. E., Durrant-Peatfield, M. R., & Levy, J. P. (2000). Conceptual structure and the structure of concepts: A distributed account of category-specific deficits. *Brain and Language*, *75*, 195–231.

Van Dantzig, S., Pecher, D., Zeelenberg, R., & Barsalou, L. W. (2008). Perceptual processing affects conceptual processing. *Cognitive Science*, *32*, 579–590.

Van Elk, M., Van Schie, H. T., & Bekkering, H. (2009). Action semantic knowledge about objects is supported by functional motor activation. *Journal of Experimental Psychology: Human Perception and Performance*, *35*, 1118–1128.

Vermeulen, N., Corneille, O., & Niedenthal, P. M. (2008). Sensory load incurs conceptual processing costs. *Cognition*, *109*, 287–294.

Vermeulen, N., Niedenthal, P. M., & Luminet, O. (2007). Switching between sensory and affective systems incurs processing costs. *Cognitive Science*, *31*, 183–192.

Warrington, E. K., & Shallice, T. (1984). Category specific semantic impairments. *Brain*, *107*, 829–853.

Wu, L., & Barsalou, L. W. (2009). Perceptual simulation in conceptual combination: Evidence from property generation. *Acta Psychologica*, *132*, 173–189.

Zanolie, K., Van Dantzig, S., Boot, I., Wijnen, J., Schubert, T. W., Giessner, S. R., & Pecher, D. (2012). Mighty metaphors: Behavioral and ERP evidence that power shifts attention on a vertical dimension. *Brain and Cognition, 78*(1), 50–58.

Zwaan, R. A., Madden, C. J., Yaxley, R. H., & Aveyard, M. E. (2004). Moving words: Dynamic representations in language comprehension. *Cognitive Science*, *28*, 611–619.

Zwaan, R. A., Stanfield, R. A., & Yaxley, R. H. (2002). Language comprehenders mentally represent the shape of objects. *Psychological Science*, *13*, 168–171.

Further Reading

Barsalou, L. W. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences*, *22*, 577–660.

Cree, G. S., & Mc Rae, K. (2003). Analyzing the factors underlying the structure and computation of the meaning of chipmunk, cherry, chisel, cheese, and cello (and many other such concrete nouns). *Journal of Experimental Psychology: General*, *132*, 163–201.

Martin, A. (2007). The representation of object concepts in the brain. *Annual Review of Psychology*, *58*, 25–45.