15

THE ROLE OF SENSORY AND MOTOR INFORMATION IN SEMANTIC REPRESENTATION: A REVIEW

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INTRODUCTION

Embodied theories of cognition propose that simulation is the basis for cognitive representation (Barsalou, 1999; Jeannerod, 2001; Hesslow, 2002; Gallese & Lakoff, 2005). Simulation is assumed to use the same sensory–motor systems that are engaged during real experience; when this principle is applied to the representation of linguistic meaning (semantics) theories propose that semantic content is achieved by recreating, usually in weaker form, the sensory and motor information produced when the referent of a word or sentence is actually experienced. Simulations are content-specific; for example, words referring to motion, such as rise and fall, are thought to recruit sensory systems involved in perceiving motion, and words referring to motor actions, such as kick and walk, are thought to recruit the motor systems used for those actions.

Therefore, embodied theories of semantic representation focus on semantic content, rather than the structure of the semantic system as a whole (e.g., distributed or localist, Dell, 1986 vs. Levelt et al., 1999), how words are related to one another (e.g., via associative connections or featural similarity, Collins & Loftus, 1975 vs. Smith et al., 1974), or how categories are represented (e.g., via modal similarity or a priori categories, Farah & McClelland, 1991 vs. Caramazza & Shelton, 1998). At a basic level, embodiment extends the non-controversial idea that we learn from experience, so semantics must be grounded in our sensations and actions; however, it appears to be a departure from the commonly accepted view that semantic content is amodal and thus not dependent on sensory–motor information (Fodor, 1987; Levelt, 1989; Jackendoff, 2002). This chapter reviews different theories of semantic representation placing them on a continuum as regards to their proposals about the role of sensory and motor information (see Figure 15.3). A brief review of behavioral and neuroscientific evidence is then presented and we end the chapter with a discussion of what the implications are for semantic representation.

DIRECT VERSUS INDIRECT ENGAGEMENT

Strong versions of embodiment assume what we refer to as the *direct engagement* hypothesis: to achieve representation, semantic content *necessarily* and *directly* recruits the sensory and motor systems used during experience. The *necessity condition* states that primary sensory and motor systems are essential for the semantic representation for concrete objects and events. The *directness condition* states that sensory and motor systems are engaged during semantic access without being mediated by other cognitive processes. One important idea here is modulation; semantic representation modulates activity in sensory or motor areas because those areas simulate the experience of the referent. Since the two share a common substrate, effects should be observed bilaterally, from language to perception/action and vice versa (see Figure 15.1).

There are several theories that subscribe to strong embodiment (see Figure 15.3). The most extreme of these is Gallese and Lakoff (2005) in which everything needed for representation (e.g., decomposition or abstraction) is considered to be present in sensory–motor systems and simulations within these modal systems underpin semantic representation. Thus, most (if not all) cognitive functions

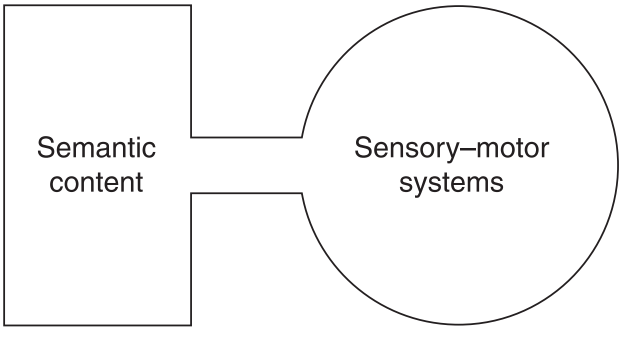

FIGURE 15.1 A schematic of direct engagement.Content-specific elements of semantic representation are isomorphic with sensory–motor systems.

are carried out *within* modal systems, creating multi-modal conceptual representation (as opposed to supra-modal systems where some information is "collapsed" across modality). Pulvermüller (1999, 2001) proposes that Hebbian learning produces embodied content: activity related to a word form occurs alongside sensory–motor activity corresponding to the word's referent, therefore, the two become associated, and sensory–motor activations become the semantic representation for a particular word. Barsalou (1999) presents a comprehensive theory of representation-as-simulation. Here, a more traditional cognitive model is presented where representations are schematic re-enactments of sensory and motor experience. However, the central tenet is the same with simulations taking place within the sensory and motor systems themselves (i.e., multi-modality). Finally, Glenberg and colleagues (Glenberg & Robertson, 2000; Glenberg & Kaschak, 2002, 2003) and Zwaan (2004) refer to the theories of Barsalou (1999) and Pulvermüller (1999), respectively when fleshing out their own theories of sentence/narrative comprehension, therefore adopting the same strong assumptions. These theories deal with both word and sentence level representations so simulation at all levels is proposed (single word, sentence, and narrative) and details of the integration of individual words, syntactic structures, and the existing context are provided. All of these theories make the following two assumptions:

1. Semantic processing automatically recruits low-level sensory and motor systems.
2. Semantic processing necessarily recruits these low-level processes (modulation), so effects should be consistent across tasks.

A weaker version of embodiment is what we will call the *indirect engagement* hypothesis. There are several possible formulations of this hypothesis, but in terms of necessity and directness it can be summarized as follows: to achieve representation, semantic content requires close contact to sensory and motor systems but activation of those systems is not necessary. The *non-essential condition* states that sensory and motor systems are implicated in semantic processing because of stable associative relationships between the semantic representation for concrete objects and events and the experience of those events. However, sensory and motor content is not necessary for semantic representation (at least once semantic representations are stable). The *indirect condition* states that sensory and motor systems are engaged during semantic access in a task-dependent manner, being mediated by cognitive processes, such as attention or perceptual learning. An important idea here is mediation; the impact of semantic representation is equivalent to an external system influencing activity in sensory or motor areas. Mediation means that bilateral effects will not always be present as the connection between semantic and sensory–motor systems is variable. Weak versions of embodiment differ from amodal theories because they assume non-arbitrary connections between semantic processing and sensory–motor systems. In contrast, amodal theories assume no direct connection: semantic processing is completely independent from sensory and motor systems (see Figure 15.2).

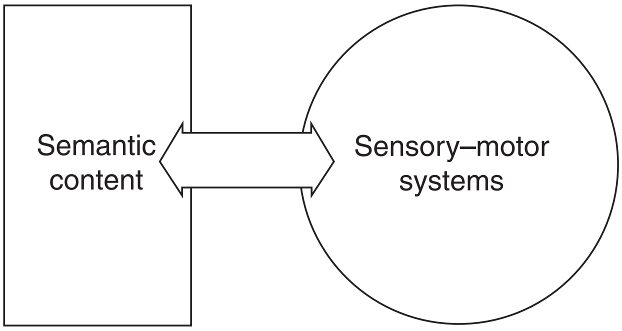

FIGURE 15.2 A schematic and indirect engagement.Content-specific elements of semantic representation are linked to sensory–motor systems in a non-arbitrary way.

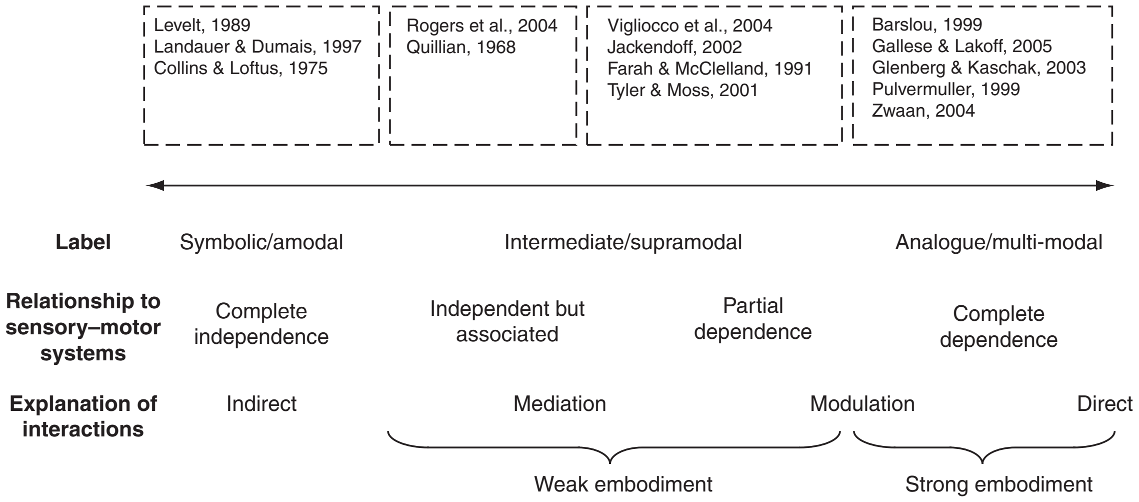

FIGURE 15.3 Schematic of theories' position along the continuum from amodal to modal.Theories are divided into four broad groups, the leftmost being symbolic/amodal theories (complete independence from and indirect interactions with modal content); intermediate supra-modal theories (associated to modal content with interactions via mediation, or partial dependence on modal content with interactions via mediation or modulation) and analog/multi-modal theories (complete dependence on and direct, modulatory interactions with modal content). Weak embodiment is claimed by intermediate supra-modal theories and strong embodiment by analog/multi-modal theories. McRae et al. (1997) and Smith et al. (1973) not included as no clear assertions are made.

There are a number of theories that adopt (or could adopt) some weak version of embodiment. Vigliocco et al. (2004) state that semantic representations are supra-modal representations that bind together modality-related conceptual features, hence they would only be partially dependent on modal systems. Jackendoff (2002) also proposes that modality-specific features are grounded in their respective modal systems whilst maintaining that much of language processing is based in an abstract, amodal conceptual structure. Other featural theories implicitly subscribe to embodiment (e.g., if their "visual" and "functional" features were grounded in the visual and motor system respectively, e.g., Farah & McClelland, 1991; Tyler & Moss, 2001). Here, the assumption would be partial dependence (i.e., supra-modality), although the precise mechanism is ambivalent between modulation and a strong form of mediation (Figure 15.3). One further step away from embodiment are theories that propose an amodal, abstract semantic system with associations to sensory–motor content (Quillian, 1968; Collins & Quillian, 1969; Rogers et al., 2004). Rogers et al. (2004) are explicit that semantic representations do not carry any content at all, but act as links to the relevant conceptual information. Quillian (1968) makes a brief reference to a common representational level between semantic and perceptual content whilst presenting a network of nodes (derived from modal content) as the basis for the semantic system. These two theories propose an independent but associative relationship where mediation is the only mechanism by which semantic and sensory–motor content can interact. For example, modality specific information could be recruited by association areas that integrate the modal information (supra-modality) and therefore have access to it. Despite the many differences across theories, they make the following weak assumptions:

1. Semantic processing is linked to sensory and motor systems but low-level sensory and motor processing is not necessarily recruited (e.g., semantic representations may be derived from higher order object concepts).
2. Modality-related effects of semantic representation are mediated so effects will vary depending on task demands (e.g., recruitment of attention and task parameters).

Finally, there are theories that propose a completely independent, amodal semantic store (Collins & Loftus, 1975; Levelt, 1989; Landauer & Dumais, 1997). Here, the link between sensory–motor and semantic content is formed outside the semantic system, by designatory processes (i.e., basic cognitive processes that link perceptions to internal representations, Pylyshyn, 1985). Here, interactions would be explained via indirect mechanisms (coming via other cognitive processes such as working memory or attention) or produced by the connection between semantic representations and the level at which designation occurs (a theoretically opaque process). Figure 15.3 summarizes where all these theories lie on the continuum from modal to amodal and which fall under weak or strong embodiment.

Below we present a review of the available evidence in light of the assumptions of direct versus indirect engagement. The strong prediction is direct engagement: to achieve representation, semantic content *necessarily* and *directly* recruits the sensory and motor systems in a simulation of the on-line experience of the referents. A weaker prediction is that semantic content recruits sensory and motor systems through association, rather than simulation. Here, the recruitment of semantic content may not be necessary but it may still be direct. Interestingly, this still predicts consistent interactions between semantic and sensory–motor information. Sensory and motor information may be recruited routinely during semantic access because of intimate ties that develop as a result of experience, but these ties do not equate to simulation.

The best way to assess the necessity constraint of direct engagement is through neuropsychological evidence or directly suppressing sensory or motor information (e.g., through transcranial magnetic stimulation, TMS).

Neuropsychological evidence is limited and currently presents a mixed picture (see e.g., Neininger & Pulvermüller, 2001; Spatt et al., 2002; Bak et al., 2006; Boulenger et al., 2008; Mahon & Caramazza, 2005, 2008) so the current review will focus on the more abundant behavioral and neuroscientific evidence that explore the directness of the connection. Associative connections (weak embodiment) should be open to more mediation than simulation (strong embodiment), so the apparent directness of the connection still allows us to distinguish someway between stronger and weaker versions of embodiment.

A BRIEF REVIEW OF THE EVIDENCE

BEHAVIORAL EVIDENCE

In a classic study, Tucker and Ellis (1998) presented pictures of objects, with affordances (potential interactions between the body and an object, for example, a handle) on the left or right. The judgments of the pictures (is it upright or inverted) were faster, and fewer errors were made, when the hand making the "upright" response and the affordance were congruent, compatible with the idea that seeing a picture of an object activates the motor actions associated with using it. Richardson et al. (2001) extended this study by presenting participants with a rapid serial visual presentation (RSVP) of eight pictured objects, with left or right affordances, followed by a decision about whether a named object was or was not in the sequence, and they found that responses were faster when the hand making the "yes" response was opposite to affordance, suggesting that the object name re-activated the motor affordances triggered when the referent object was perceived. However, it could be that the semantic content of the object name only accesses task-based affordances produced by object–picture perception. Myung et al. (2005, Experiment 1) addressed this issue by using an auditory lexical decision task in which primes did or did not share affordances with the target word, for example, a typewriter and a piano are both manipulated through fine pressing movements of the fingers. Lexical decisions were faster when the prime shared affordances with the target, supporting the automatic activation of motor plans upon semantic access. Siakaluk et al. (2007) provided further support for this by using target words that were previously rated on how easy or hard they were to physically interact with (a Body–Object Interaction score, BOI). Participants performed either a lexical or a phonological decision task and results showed that in both the tasks, decisions were faster for high BOI words as compared to low BOI words. The authors concluded that semantic representations include information about sensory–motor experience, on the assumption that high BOI words have "more" of this information. Two studies reinforce the inference that motor information accessed during semantic processing is based in the motor system itself by demonstrating that single-word comprehension of action verbs interacts with the motor system. Tseng and Bergen (2005) used

American Sign Language and showed that signs with semantic or metaphorical motion mirrored in a physical movement toward or away from the body were judged faster when the decision response was in a congruent direction (toward or away from the body). Signs with only phonological motion did not show the congruency effect. Boulenger et al. (2006) showed that reaching responses required to make a lexical decision, with the word appearing once the movement had been initiated, had smaller acceleration peaks when the word referred to an action as compared to a concrete nouns (suggesting interference). In contrast, when the item was presented as the go signal, peak accelerations were earlier for action verbs than for nouns (suggesting facilitation). Thus, motor information was activated early in comprehension, interfering with motor actions when concurrent and facilitating actions when precedent.

Klatzky and colleagues (1989) found that presentation of a congruent action cue speeded sensibility judgments for action sentences, for example, the cue for a flat palm followed by the sentence "rub your stomach." The same priming effects were found when subjects made a button press or verbalized their response for the sensibility judgment. Crucially, the effects were removed when motor tapping, but not syllable repetition, was used as a secondary task: that is, the preparation for the tapping task abolished the facilitation from preparing the hand shape (McCloskey et al., 1992). Similarly, reaction times to judge sentences that describe motor actions toward or away from the comprehender were found to be faster when the response was congruent with the described action; this is known as the Action Sentence Compatability Effect (Glenberg & Kaschak, 2003), and it has been shown to be dependent on timing, such that it is only present when preparation of the response is concurrent with sentence comprehension (Borreggine & Kaschak, 2006). Expanding on these results, two studies in Italian have shown interactions between the effector used for responding (hand, foot, or mouth) and the judgment of action sentences specifying those effectors. Buccino et al. (2005) used a hand (button) or foot (pedal) response, demonstrating that reaction times were slower when the response and effector described in the sentence were congruent. Scorolli and Borghi (2007) used a mouth (verbal) or foot (pedal) response and found sensibility judgments for pairs of nouns and verbs were faster when the effectors were congruent. The difference between interference and facilitation may be due to the response being prepared during the sentence (Buccino et al., 2005) or after it has been presented (Scorolli & Borghi, 2007) as in Boulenger et al. (2006). Finally, in a set of elegant experiments, Zwaan and Taylor (2006) found that sensibility judgments for sentences containing implied manual rotation, for example "Jane started the car," were faster when responses were made by turning a knob in the same direction as the implied rotation. Congruent facilitation was also found (but only at the verb region where the direction of rotation is specified) when participants smoothly turned a knob to progress through implied rotation sentences in self-paced reading. The use of "motor resonance" between the visual and motor domains extended these results when it was shown that the perception of congruent visual rotation speeded the judgment and reading (at the verb) of manual rotation sentences (see Fischer & Zwaan, in press, for an extensive discussion on motor resonance in comprehension). Thus there is cogent support for a semantic system that has access to effector specific motor information that is relevant to particular referents (i.e., manipulable objects and body actions); this does support a direct connection between motor semantics and motor information.

Outside the motor domain a similar picture is beginning to emerge but the evidence is more variable. Zwaan and Yaxley (2003) presented pairs of words for speeded similarity judgments; the critical items were pairs that referred to objects with a canonical spatial relation where one is above the other (e.g., root–branch, floor–ceiling). Reaction times were faster when the visual presentation of the words was congruent with the canonical relation (e.g., root at the bottom and branch at the top) rather than incongruent (e.g., root at the top and branch at the bottom). A series of experiments with a similar motivation explored whether visual attention was similarly affected by comprehension (Estes et al., in press): participants were presented with a category word (e.g., cowboy) and a part word (e.g., boot or hat) that was located at the top or bottom of the object. Following the presentation of the part word, participants identified a target letter presented in a congruent or incongruent location to the part word (i.e., top or bottom of the visual field). They found that letter identification was slower when the target location was congruent; this finding was replicated when the part-words were presented alone. Thus, the semantic content of words referring to concrete nouns with a canonical location interacts with visuo-spatial processing. In a different manipulation of visual properties, Pecher et al. (1998) manipulated the relationship between the prime and the target in a semantic priming task according to the similarity of their referents' visual form (e.g., pizza–coin, honey–glue). A small perceptual form priming effect was found for word naming when the prime referent shared visual form with the target, but only when the naming task was preceded by a perceptual decision task, which made the item's form salient (i.e., whether the word referred to an oblong object). Hence, these results do not support a direct link. Studies using sentence stimuli have supported interactions with visuo-spatial and motion processing. Richardson et al. (2003) displayed pairs of object pictures centrally as they were concurrently described in an aurally presented sentence that described a vertical ("The ship sunk in the ocean") or horizontal ("The mechanic pulled the chain") event; subsequent recognition of the pairs (i.e., were these two pictures seen in the same sentence?) was faster when they were presented in a spatial orientation congruent with the sentence. Post hoc analyses showed that the effect was significant for concrete, but not abstract, sentences. When the same sentences were presented before categorization of a shape in the vertical (top or bottom) or horizontal (left or right) meridian, categorization was slower when the visuo-spatial location and sentence orientation were congruent. These results have been replicated for concrete sentences describing upward and downward motion or objects with a canonical location "up" or "down" (e.g., ceilings or cellars) (Bergen et al., 2007). This suggests that visuo-spatial attention may only be influenced when a concrete location (provided by a concrete object) is defined, providing a potential target. This explanation contrasts with the one where a necessary simulation of all semantic representations (concrete and abstract) is similar to conscious visual imagery (Richardson et al., 2003; Bergen et al., 2007).

Stronger support for the connection between visual and semantic motion comes from studies showing that the comprehension of aurally presented sentences that describe vertical or egocentric motion is slowed when congruent visual motion is perceived (Kaschak et al., 2005). In an extension of the original experiment, Kaschak et al. (2006) found that when the motion and sentence stimuli (now describing auditory motion events) were presented in the same modality (e.g., both aurally), reaction times showed congruent facilitation. However, when presented in different modalities (i.e., visual sentences via RSVP and auditory motion stimuli), reaction times showed congruent interference. The authors proposed that when the two are presented in the same modality they are processed serially, producing congruent facilitation (priming), whereas presentation in a different modality results in concurrent processing and congruent interference (taxing the same resources). In contrast to this explanation, but in line with embodiment, Meteyard et al. (2007) showed that comprehension of blocked single words referring to motion (e.g., rise, climb, ascend) impaired the detection of concurrent motion signals (set at the threshold of conscious perception) when the two were incongruent (i.e., upward and downward motion), as shown by lower d' values. Crucially, no effects were found in reaction times and a measure of decision threshold (c) showed reduced values under congruent conditions (suggesting decision priming). These results show incongruent interference at low levels of perception (d'), and congruent facilitation at higher levels (c). In support of incongruent interference between semantic motion and low-level motion processing, Meteyard et al. (in press) found that motion patterns at the threshold of perception (assumed to be obligatorily processed) produced longer reaction times for lexical decision on motion words when the two were incongruent (i.e., "rise" with a downward motion pattern). Crucially, salient motion signals produced no congruency effects (supporting the inference that they are suppressed by top-down mechanisms; Tsushima et al., 2006). These results suggest that the relationship between semantic and perceptual information is complex, supporting a mediated connection and weaker versions of embodiment.

Several studies have used property verification, for example, is "feathers" a property of "pigeon"? and it is assumed that conceptual representations are accessed for this task to be performed and when the stimuli are words, we assume that the semantic representation of the word is accessed too. The data from property verification is quite consistent, showing effects of the perceptual modality and spatial location of the property. Reaction times are faster when the current trial modality (e.g., blender-loud) was the same as for the previous trial (e.g., leaves-rustle) rather than different (e.g., soap-perfumed) (Pecher et al., 2003). This modality switching cost is also present when the same *concept* is presented in successive trials with properties in the same or different modality (Pecher et al., 2004). Marques (2006) showed that the modality switching cost was present even when category (living vs. non-living) was kept constant. These results support simulation as there is a cost analogous to the cost of attending to events in different modalities during an on-line task (Spence et al., 2001). Property verifications are also faster when the concept is presented in a sentence, which implies a particular perspective (e.g., standing near the front or back of a car), and the property is salient given that perspective (e.g., the hood or trunk of the car respectively). This was also found when the property was at the top or bottom of a concept (e.g., the hair or shoes of a doll) and the response was made with a congruent response action, that is, pressing the top or bottom button on a response box (Borghi et al., 2004). Finally, a regression analysis showed that more variance in reaction times for property verification was accounted for by perceptual (read embodied) properties of a concept, when filler items precluded the use of simple word association strategies (Solomon & Barsalou, 2004). One criticism of these studies is that all property verification tasks may invoke imagery or more conscious processing than is typically required for semantic access: participants have to make an explicit judgment. Therefore, these tasks may not be representative of normal semantic processing. However, it does provide support for a somewhat direct connection between semantic and sensory–motor information.

A series of experiments, mostly conducted by Zwaan and colleagues, have used picture judgments to explore perceptual simulation in language comprehension. All experiments present target pictures following the comprehension of sentences. The consistent finding is that when pictures are congruent with the preceding sentence, their recognition or naming is facilitated. This has been demonstrated for congruence in object orientation (Stanfield & Zwaan, 2001), object form (Zwaan et al., 2002), and apparent motion (Zwaan et al., 2004). When color congruence was manipulated, slower responses were found for congruent conditions, this was tentatively explained by the instability of color representations in visual processing (Connell, 2006). In addition to the evidence from sentence comprehension, there is substantial evidence that narrative comprehension engages analog visuo-spatial and temporal representations (Zwaan, 1999 or Zwaan & Radvansky, 1998 for a review; Rinck et al., 1997; Rinck & Bower, 2000; Horton & Rapp, 2003; Kaup & Zwaan, 2003; Kaup et al., 2006). Nevertheless, there is only preliminary evidence that visuo-spatial processing interferes with narrative comprehension (Fincher-Kiefer, 2001), so whilst it is clear that situation models can be seen as embodied simulations, it is still possible to explain the results with an associative amodal network (Rinck & Bower, 2000).

Stronger evidence for the activation of perceptual information during comprehension comes from eye movement studies that we only briefly summarize here: when participants are asked to actively imagine or to simply listen to scene descriptions, their eye movements reflect the implied location of events (Spivey & Geng, 2001; Matlock & Richardson, 2004). This is in line with an embodied interpretation where the eyes move as if those events were being observed. Eye movements also provide evidence that perceptual and motor features of individual words are active during comprehension (Dahan & Tanenhaus, 2005; Myung et al., 2005). This provides support for perceptual and motor features being a part of semantic representation (see also Spivey et al., 2000; Chambers et al., 2002, 2005; Laeng & Teodorescu, 2002). Eye movements are an increasingly useful tool to explore comprehension (for a review see Henderson & Ferreira, 2004) and through the use of inventive methodologies, they are also supporting the role of perceptual and motor information in semantic representations. One small caveat is that eye movements may not be a veridical mirror of the mind, directly reflecting the immediate contents of cognitive processing. The mechanisms that influence oculo-motor movements, such as attention, imagination and task-demands, need to be better understood before eye movement studies can provide strong evidence for embodiment.

NEUROSCIENTIFIC EVIDENCE

Neuroscience has held "embodied" views for a long time: concepts are defined by sensory and motor attributes that arise from experience, when we see, hear, touch, and manipulate things in the environment. Distributed feature networks of sensory and motor attributes will be reflected in sensory and motor cortices of the brain; for example, the ventral occipital cortex (fusiform gyrus) supports knowledge about object form and the lateral temporal cortex (MT) supports knowledge about object motion (Martin & Chao, 2001). Neuropsychological and neuroimaging studies typically use verbal labels as one of several access routes to conceptual information (similar to pictures, e.g., Martin & Chao, 2001; Plaut, 2002; Rogers et al., 2004) rather than exploring intermediate semantic representations (Damasio et al., 1996). As such, neuroscientific theories do not typically explore the division between conceptual and semantic information (Damasio, 1989; Farah & McClelland, 1991; Martin & Chao, 2001; Tyler & Moss, 2001; Plaut, 2002; for an exception see Damasio et al., 1996, 2004), allowing modality specific content into "semantics" without much consternation about embodiment. This contrasts with cognitive/psycholinguistic theories that build on a classical cognitive heritage (Newell, 1980; Pylyshyn, 1985; Fodor, 1987) and typically propose some division between conceptual and semantic information that allows amodal semantics to be extracted from modal concepts.[1] Although there is necessary overlap (Farah & McClelland, 1991; Tyler & Moss, 2001), it is outside the scope of this chapter to explore the debate in neuroscience and neuropsychology about the organization of the conceptual system[2]; but the debate does

[1] For a marginal separation see McRae et al. (1997); partial separation see Jackendoff (2002) and Vigliocco et al. (2004); and complete separation see Levelt (1989) and Levelt et al. (1999).

[2] Briefly, the debate rages over where to draw the major fault lines in conceptual content; is it by modality (e.g., visual and functional features), domain (e.g., the categories of animals and fruit/vegetables), or some other systematic structure (e.g., Warrington & McCarthy, 1983, 1987; Warrington & Shallice, 1984; Caramazza et al., 1990; Shallice, 1993; Humphreys & Forde, 2001; Martin & Chao, 2001; Caramazza & Mahon, 2003).

show us that sensory and motor information has been implicated in (at least) conceptual representation for a long time. For example, in Convergence Zone Theory (Damasio, 1990; Damasio & Damasio, 1994) primary sensory cortices contain featural components and basic combinatorial arrangements of those features (parts, shape, color, movement, etc.). More complex combinatorial codes, which define the perception of events (spatial and temporal relationships) are "inscribed" (p. 127) in higher order association areas (frontal and temporal cortices), called convergence zones (Cz). Thus, the physical properties of experience are represented in the primary cortices, but their synchronized activation and co-ordination depends on feedback connections from Cz. Thus, embodied theories represent a strengthened version of existing ideas in neuroscience; for example, proposing multi-modal direct engagement without the need for higher order, progressively supra-modal associations (Barsalou, 1999; Pulvermüller, 1999; Gallese & Lakoff, 2005) or building on Cz theory with embodied neural principles (Simmons & Barsalou, 2003[3]).

The strength of the neuroscientific evidence for embodiment depends on modality (but see Kemmerer et al., in press). The premotor and motor cortices are consistently activated across studies and methods. These cortical areas are not only seen for language referring to body actions (Pulvermüller et al., 2000, 2001, 2004; Tettamanti et al., 2005; Aziz-Zadeh et al., 2006; Vigliocco et al., 2006), but also for tool actions and tools/manipulable objects (Grabowski et al., 1998; Chao & Martin, 2000; Gerlach et al., 2002). TMS studies provide converging evidence that lexical and sentential items with motor associations activate motor areas of the cortex (Oliveri et al., 2004; Buccino et al., 2005) and localized motor cortical areas corresponding to the specific effector of an action (Buccino et al., 2005; Pulvermüller et al., 2005). The timing of the TMS, early in the time-course of comprehension and production, supports the argument that modality specific activations are part of the early lexico-semantic processes. For most of the studies, the motor activation is left lateralized, although there is some evidence that the right hemisphere is implicated for tool action generation (e.g., Damasio et al., 2001). This strongly suggests that the motor cortex plays a role in the semantic representation of objects and actions with salient motor associations. Simulation during comprehension is supported by effector specific manipulations (Pulvermüller et al., 2005; Aziz-Zadeh et al., 2006), which suggest that the motor cortex is selectively recruited depending on the content of the language. Alongside the motor cortex, MT activity is repeatedly seen for body and tool actions as well as tool objects[4] (Martin et al., 1995, 1996; Damasio et al., 2001; Phillips et al., 2002; Tettamanti et al., 2005). When activity in this area is observed for tools and tool actions, it is usually explained as a reflection

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[3] Simmons and Barsalou (2003) extend Cz theory with the Similarity in Topography (SIT) principle (see Plaut, 2002, for a very similar, but computational, approach). Here, the actual cortical proximity of convergence zones is dictated by their similarity, which is in turn dictated by the modalities (visual, motor, etc.) and/or properties (shape, color, movement) of the features they conjoin.

[4] This may be related to stimuli in these experiments being pictures rather than word stimuli.

of knowledge about the movement of objects during their use (Phillips et al., 2002). This is also in line with accounts that propose modality specific areas (in this case, those processing visual motion) are implicated in the representation of knowledge from that modality. Despite the fact that MT is typically understood as a motion processing area, there is only one study that has used motion sentences (both literal and fictive) and the active area in this case was proximal, but not isomorphic, with MT (Wallentin et al., 2005). Finally, the Amygdala supports "modality" specific representation, being active for threat words (Isenberg et al., 1999). Evidence from the motor/action domain is, therefore, in line with strong and weak embodied theories where sensory–motor features are represented multi-modally or via associations with the sensory–motor cortices; the TMS evidence lends weight to the directness of this connection, and possibly its necessity.

Beyond body actions, tool actions, and tools, the evidence is considerably less coherent. EEG data have shown attenuation of the N400 (typically interpreted as responding to semantic incongruence) when targets where preceded by visual-form related primes (Kellenbach et al., 2000). The fusiform gyrus is documented as playing a role in the representation of object form (Chao et al., 1999; Vuilleumier et al., 2002) and different areas of the fusiform have been implicated for different categories, that is lateral fusiform for animals and medial fusiform for tools (Martin & Chao, 2001). Fusiform activity was observed for tool and animal names relative to a nonsense object baseline (Martin et al., 1996), for conceptual access during property verification for objects (Kan et al., 2003), and for words related to form and color (Martin et al., 1995; Pulvermüller & Hauk, 2005). For sensory words in general (e.g., darken, darkness), an area proximal to the fusiform was observed (Vigliocco et al., 2006). These results support the role of the fusiform in representing the visual attributes of known objects, and more generally this area of the cortex as involved in higher order visual association; combining features from different modalities (Vigliocco et al., 2006). As regards to embodiment, fusiform activation is not that informative. It can be taken as a predominantly visual area, therefore supporting modality specific representation (multi-modality), but its role as an area that represents objects regardless of idiosyncratic variations in appearance (e.g., Vuilleumier et al., 2002) suggests that it responds to combinations of features or attributes to provide a more abstract representation of objects: thus, being a supra-modal rather a multi-modal area.

It is of course crucial whether the cortical areas implicated in semantic representation are isomorphic with the cortical areas involved in experience, as this is the strong version of embodied simulation when it is applied to neural structures. But higher order association areas are problematic for strong embodiment, which predicts the concurrent activation of different modality specific areas rather than concentrated activity in one area that is connected to these modal systems. It is an open question whether supra/hetero-modal areas that combine information across modalities still constitute embodied representations, or whether they indicate a progression from modality specific to modality invariant (and ultimately modality independent) representations (see Kemmerer et al., in press, for some evidence for multi-modal activations).

It is clear that language referring to objects and actions with a salient modality (e.g., tools or body actions) activate cortical areas involved in the experience of that modality. However, this can be taken as support for weaker versions of embodied theories that do not necessitate simulation, or full embodiment. It is always possible that sensory and motor cortices become active in a secondary manner, incidental to necessary processing in semantics; however, the evidence of early modal activity shown in TMS and EEG speaks against this conclusion (Pulvermüller et al., 2001, 2005). The isomorphism between the cortical areas used during real-world experience and semantic representation is supported for the motor cortex, but it is less clear what the literature shows for non-motor information. It is worth noting that the motor cortex has a special status as an efferent area that responds to top-down commands (such as verbal instruction), therefore what applies there may not apply for afferent sensory areas that respond to sensory stimuli.

CONCLUSIONS

As stated in the "Introduction" paragraph, the strong prediction from embodied theories of semantic representation is the *direct engagement* hypothesis: to achieve representation, semantic content *necessarily* and *directly* recruits the sensory and motor systems used during experience. The necessity condition states that without the support of sensory and motor systems, semantic representation for concrete objects and events is impaired. The directness condition states that sensory and motor systems are engaged during semantic access without being mediated by other cognitive processes. So, what can be concluded about the necessity and direct engagement of sensory and motor systems in semantic representation?

Neuroscientific evidence reliably shows motor cortex activation for tools, tool actions and body actions (Gerlach et al., 2002; Tettamanti et al., 2005), but the evidence for other domains is less consistent (e.g., Pulvermüller & Hauk, 2005; Vigliocco et al., 2006; Kemmerer et al., in press). However, brain activity (particularly in fMRI/PET) is always correlational rather than causal. Sensory and motor activity could be the result of the high association between particular semantic domains and particular modalities, rather than the result of direct engagement in representation.

One important correlate of automaticity is speed: the faster the access to sensory and motor information, the more likely it is to be a typical and elemental part of semantic processing (Pulvermüller, 2001). There is evidence of fast access to motor information during comprehension (Pulvermüller et al., 2000, 2001; Boulenger et al., 2006) and behavioral studies as the motor domain do support timing as a crucial element (Borreggine & Kaschak, 2006; Zwaan & Taylor, 2006). Numerous reaction time studies show the influence of sensory–motor semantic content on sensory or motor processing, and neuroscientific evidence shows sensory and motor activation following both active and passive comprehension. However, unless low-level processes are directly tapped (Meteyard et al., 2007, in press), results could still be contaminated by decision or some other mediating processes (such as imagery, attention, or a task-set, which sets up implicit relationships between linguistic and sensory/motor manipulations). In contrast, if sensory or motor activity is shown to affect comprehension, it is harder to explain away these effects by mediating processes. Such evidence is available for the motor domain (Glenberg & Kaschak, 2003; Zwaan & Taylor, 2006) and TMS studies show that direct activation of the motor system affects the comprehension of motor words (Pulvermüller et al., 2005); but evidence is limited for the senses (Kaschak et al., 2005, 2006; Meteyard et al., in press).

So far, a few studies have directly manipulated low-level sensory processes. These results show that the perception of motion affects the comprehension of motion sentences (Kaschak et al., 2005) and words (Meteyard et al., in press) and another which shows influences of motion words on low-level motion perception (Meteyard et al., 2007). But there is preliminary evidence that the influence of motion perception on comprehension may be task dependent (Meteyard et al., submitted), suggesting an automatic but mediated connection.

The evidence for sensory–motor information in semantic representation is growing, with increasing evidence that there is a direct connection between systems involved in sensory–motor experience and the representation of sensory–motor content in language, but the question of necessity is unanswered. This argues strongly against theories of semantics, which propose complete independence between semantic and sensory–motor information. More complex questions about the precise nature of the connection remain to be mapped out, with strong and weak embodiment holding equal explanatory potential at the present time.

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16

EMBODIED CONCEPT LEARNING

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HOW CONCEPTS ARE LEARNED

We address the question "How do people learn new concepts?" from the perspective of Unified Cognitive Science. By Unified Cognitive Science, we simply mean the practice of taking seriously all relevant findings from the diverse sciences of the mind, and here we are focusing on the question of concept learning. The particular perspective on concept learning advocated here grows out of the Neural Theory of Language project (www.icsi.Berkeley.edu/NTL), but is compatible with most cross-disciplinary work in the field.

Leaving aside for now Fodor's (1998) argument that concepts cannot be learned (which turns on disputable definitions of *learn* and *concept*), concept learning poses an ancient and profound scientific question. If we exclude divine intervention, then there are only two possible sources for our mental abilities: genetics and experience. There is obviously something about our genetic endowment that enables people, but not other animals, to become fluent language users and possessors of human conceptual systems. As nothing can enter our minds without intervention of our senses, which are themselves in large part the product of genetics, nature must provide the semantic basis for all the concepts that we acquire. So, in some sense, people really cannot learn any concepts that go beyond the combinatorial possibilities afforded by genetics.

At the same time, the conceptual systems of individual humans are profoundly marked by their experience—from maternal vocalization while still in the womb (Moon et al., 1993) to experience with culture-specific artifacts like