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Semantic embodiment, disembodiment or misembodiment? In search of meaning in modules and neuron circuits

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ABSTRACT

"Embodied" proposals claim that the meaning of at least some words, concepts and constructions is grounded in knowledge about actions and objects. An alternative "disembodied" position locates semantics in a symbolic system functionally detached from sensorimotor modules. This latter view is not tenable theoretically and has been empirically falsified by neuroscience research. A minimally-embodied approach now claims that action–perception systems may "color", but not represent, meaning; however, such minimal embodiment (misembodiment?) still fails to explain why action and perception systems exert causal effects on the processing of symbols from specific semantic classes. Action perception theory (APT) offers neurobiological mechanisms for "embodied" referential, affective and action semantics along with "disembodied" mechanisms of semantic abstraction, generalization and symbol combination, which draw upon multimodal brain systems. In this sense, APT suggests integrative-neuromechanistic explanations of why both sensorimotor and multimodal areas of the human brain differentially contribute to specific facets of meaning and concepts.

1. Introduction

Semantic and conceptual information is, at least in part, based on information in action and perception systems of the brain and mind. This position has sometimes been called semantic "grounding". All well-developed "embodied" theories adopt such semantic grounding in action and perception information, but also discuss mechanisms not specific to individual modalities which make additional contributions to semantic and conceptual processing (for example, Arbib, 2008; Barsalou, 1999, 2008; Fischer & Zwaan, 2008; Gallese & Lakoff, 2005; Glenberg & Gallese, 2012; Kiefer & Pulvermüller, 2012; Meteyard, Cuadrado, Bahrami, & Vigliocco, 2012; Pulvermüller, 1999; Pulvermüller & Fadiga, 2010). In Barsalou's proposal, perceptual information processed in sensory systems along with resultant activation in multimodal systems jointly contribute to bottom-up concept processing (Barsalou, Kyle Simmons, Barbey, & Wilson, 2003). In my own proposals, neuronal circuits (cell assemblies) distributed over sensory, motor and multimodal association areas are the neurobiological correlates of meaningful words and constructions (Pulvermüller, 1999). A key concept is that of semantic circuits: cell assemblies that bind modality specific semantic information into a more abstract multimodal, and therefore in a sense "amodal"[1] and "modality-unspecific", representation (Fuster, 1995; Pulvermüller, 2012). These semantic circuits are widely distributed and can reach into modality-specific and multimodal areas of cortex. Crucially, semantic circuit topographies (their distributions over the cortex) can reflect aspects of the category-specific meanings they carry. As I explain in Section 3 below, this theoretical perspective covers all aspects of cognition sometimes claimed to be missing from some versions of embodiment theory, including mechanisms for abstraction, generalization and symbol combination.

A so-called "disembodied" perspective has been proposed according to which semantic representations and processes are located exclusively in amodal mind and brain systems. In this modular perspective, sensory and motor processes are viewed as being entirely "ancillary" to meaning and concepts. However, on the basis of theoretical arguments and recent evidence – for example the semantically specific influence of motor action on abstract sentence semantics (Glenberg, Sato, & Cattaneo, 2008) or the causal effect of magnetic stimulation of arm/leg motor areas on the

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[1] I normally tend to avoid the term "amodal" in this context, for reasons similar to those for calling a multilingual person multilingual and not alingual (or aphasic).

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processing of semantic subclasses of action-related words used to speak about arm or leg actions (Pulvermüller, Hauk, Nikulin, & Ilmoniemi, 2005) – it is now generally acknowledged that action and perception systems, possibly interacting with additional multimodal (or "amodal") systems, can make semantically-specific contributions – at least to the processing of some semantic aspects of at least some words and constructions.[2]

However, this new evidence does not force one to adopt standard embodiment accounts. Coming from a modularist tradition, one may prefer a strategy to design a theory that builds on an amodal semantic system and just gives way to alternative proposals as much as it must under the pressure of the data. A disembodied approach with just a grain of embodiment has been proposed by Caramazza and his colleagues (for example, Bedny & Caramazza, 2011; Mahon & Caramazza, 2008). This present paper will discuss disembodiment along with such minimal-compromise positions (part 2), highlight their difficulties, and review an alternative, a view on abstract semantic mechanisms grounded in concrete neuronal brain circuitry (part 3). Relevant evidence is discussed throughout and is the focus of the final section (part 4).

2. Embodiment vs. disembodiment: multiple confusions

Theories are sometimes called *embodied*, because they ground cognitive processes in bodily action and perception (Barsalou, 2008; de Vega, Graesser, & Glenberg, 2008; Fischer & Zwaan, 2008; Kiefer & Pulvermüller, 2012; Meteyard et al., 2012). Note again that this position implies that action and perception mechanisms play a role in the semantics of at least some words, symbols and constructions, but it does not preclude other (nonmotor and nonsensory) mechanisms to contribute to semantics. Models including a semantic module encapsulated from action and perception systems are key examples of *disembodiment*. In modular models, conceptual/semantic, action and perception systems are each thought to be informationally encapsulated from each other, therefore excluding a direct contribution of action and perception information to meaning representation (Fodor, 1983). Consequently, action and perception mechanisms are not considered semantic (Mahon & Caramazza, 2008).

The above explanations of the terms "embodiment" and "disembodiment" may be shared by some, perhaps most, in the field, but they are not agreed upon generally. As a consequence, it is sometimes not clear what the dispute about embodiment is actually all about. Upon recent reviews highlighting the embodiment debate, the present section will specifically discuss misrepresentations of embodiment ideas ("misembodiment") and recent proposals of "minimal embodiment".

2.1. Confusions about embodiment: misembodiment

Caramazza and his group did not frame the contrast between embodiment and disembodiment as explained above. In their view, *embodiment* means "that conceptual content is reductively construed by information that is represented within the sensory and motor systems" (p. 59, Mahon & Caramazza, 2008) and "that concepts are no more than a recapitulation of sensorimotor experiences" (Caramazza, NLC2011 abstract). This vision of "embodiment" is not appropriate if it is meant as a description of current approaches. Not a single one of the major approaches to conceptual and semantic mechanisms shares these assumptions. As embodiment positions are fundamentally misrepresented by Caramazza and his colleagues, I will speak about *misembodiment* in this context.[3]

Caramazza et al.'s misrepresentation of embodiment theories leads these authors to state that, according to one of the key papers in the field of embodied cognition (Barsalou, 1999), concepts are "no longer embodied" (p. 68, Mahon & Caramazza, 2008). This is because, in Barsalou's model, convergence zones in "higher" association cortex receive a role in multimodal integration of information and concept processing, a key feature of this and most other models currently treated under the "embodiment" label. In my own work, I drew attention to the fact that the functional properties of neuron circuits enable them to approximate logical operations, including AND and OR,[4] a well-known fact which has been emphasized early for abstract neuron models (see Kleene, 1956; McCulloch & Pitts, 1943) and more recently for interlinked neuronal assemblies (e.g., Buzsáki, 2010; Hayon, Abeles, & Lehmann, 2005; Palm, 1982; Pulvermüller, 2002b; Wennekers, Garagnani, & Pulvermüller, 2006; Wennekers & Palm, 2009). Therefore, neuronal machines can easily accommodate abstract symbolic processes. If there are neuronal assemblies with strong links into cortical areas important for action and perception, which can therefore be called "embodied", these same circuits can certainly, at the same time, serve their normal function as "symbolic" processors. Such circuits would obviously do more than "recapitulating sensory experiences" although they would still be, in a sense, "embodied". In my view, many distributed neuronal sets carrying semantic function are both "embodied" and symbolic.

2.2. Confusions about the role of action perception circuits

Similar to disembodiment, Mahon and Caramazza propose "an 'abstract' and 'symbolic' level of conceptual content (...) not constituted by sensory and motor information". In Caramazza et al.'s hands, sensorimotor systems are allowed to functionally contribute to conceptual or semantic processing, although this contribution is described, rather metaphorically, as "coloring" or "dressing" the concept (p. 68f, Mahon & Caramazza, 2008). However, there is some lack of clarity as to what the terms "coloring" and "dressing" mean in this context. In line with the observation that colors and dresses can be put on an object but are not part of the object, Bedny and Caramazza further stress the idea of abstract concepts in "modality-independent" areas, now arguing *against* a role of sensorimotor systems in conceptual processing (Bedny & Caramazza, 2011). It therefore appears that, in this perspective, action and perception systems are seen as capable of changing the *appearance* (color, dress) of concepts, but not of changing their *essence*, which is contained in the "amodal" symbolic system.

As sensory and motor information is not viewed as "constitutive" or fundamental, removal of these systems should be possible without affecting conceptual or semantic content. However, the authors' statements in this context are vague. They write that "'removing' the sensory and motor systems (as in brain damage) would result in impoverished or 'isolated' concepts" and in this sense the "activation of sensory and motor processes during conceptual processing is not necessarily 'ancillary to' or 'inconsequential for' conceptual processing" (p. 68, Mahon & Caramazza, 2008). Note that these statements suggest a deficit, but are compatible

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[2] Please note that there are signs that do not directly relate to objects and actions – most notably grammatical function words along with grammatical affixes (Pulvermüller, 1999) – and that even for very clearly object- or action-related expressions there are semantic aspects not captured by object or action links (Frege, 1980; Pulvermüller, 2012).

[3] To preclude any confusion: By "misembodiment", I mean misconceptions about embodiment and grounded cognition.

[4] As neurons are probabilistic devices, it is best to think of their symbolic capacities in terms of probabilistic logic.

with an exegesis that "isolated concepts" without sensorimotor "dressing" are fully intact and functional. Still, a further statement is that "sensory and motor information, on that view, contributes to the 'full' representation of a concept", now implying that, if sensory and motor systems are missing and cannot contribute, the concept will not be "full" any longer, thus being impaired. But would the presumed impairment of the concept be significant or rather superficial? These statements are open to a wide range of possible interpretations and especially to the position that, whatever might go on in action and perception systems of the mind and brain, their lesion could at best remove some minor amount of superficial conceptual information. In sum, sensory and motor systems may contribute to, in a "dressing" sense, but are not constitutive and necessary for, concepts and meanings (Mahon & Caramazza, 2008). They would function as optional enrichment and coloring while not being essential.[5]

Why is there an influence of specific hand/arm movements on the processing of specific types of abstract sentences (Glenberg et al., 2008)? Why should magnetic pulses to the foot region influence the processing of leg-related action words such as "walk" or "run" (Pulvermüller, Hauk et al., 2005)? Why would the leg motor system light up already 100–200 ms after speech input first provides the information about an upcoming leg-related action word (Pulvermüller, Shtyrov, & Ilmoniemi, 2005)? And should the motor system instantaneously kick in in abstract meaning understanding, for example when subjects hear about somebody "kicking the bucket" (see Boulenger et al., 2012) – or should it not? Such predictions and explanations were provided by specific grounded-neurocognitive models (see Sections 3 and 4), and the sometimes unexpected results have made life difficult for classic modular and "disembodied" theories. In the context of Caramazza et al.'s minimally-embodied approach, it remains to be clarified which data sets are predicted and explained, and how the explanations actually work. At present, the "dressing" or "coloring" function of action and perception systems seems to contrast with data on causal effects on and impairments of semantic-category-specific processes brought about by stimulation and lesion of sensorimotor cortex (Sections 4.3–4.4).

2.3. Confusion about functional interaction

For systems of encapsulated modules, there is no problem in localizing cognitive functions (e.g. understanding) in one module but not in others. Mahon and Caramazza illustrate this using Levelt's modular model of speech production where information is allowed to cascade from semantic down to phonological modules – without any pathway for travelling back (Levelt, 1989; Levelt et al., 1991; Mahon & Caramazza, 2008). In this context, it makes sense to see semantics being processed in the semantic module and any activation reaching the phonological module as overspill from semantics, which is unable to contribute further to semantic processing. However, as soon as reciprocal and dynamic interaction is introduced, such functional separation becomes impossible; phonological and semantic information interact dynamically across phonological and semantic nodes (Dell, 1986; Dell, Schwartz, Martin, Saffran, & Gagnon, 1997). Therefore, an interactive framework allows semantic mechanisms to be effective in and to be influenced by other processing components.

Importantly, Caramazza and his colleagues argue against modularism and disembodiment in its purest form: "language, perception, and action are not isolated modules but interact dynamically" (p. 92, Bedny & Caramazza, 2011). This statement is great news and indicates that the major argument bolstered by data from language–action interactions have finally contributed to a more general rejection of modularist positions (see also Pulvermüller, 2005). The acknowledged interactive nature of language, action and perception processing implies that action, perception and linguistic – including "modality-independent" semantic – systems *exchange information*. Given agreement on this major issue has now been achieved, it is indeed important to explore the hypothesis space and find consistent models that explain relevant new data sets. Unfortunately, however, Caramazza and his colleagues still maintain that "understanding the word "run" occurs in modality-independent neural systems" (p. 92, Bedny & Caramazza, 2011) – and thus *outside of* areas crucial for action and perception, such as higher sensory and premotor cortex. Is there a degree of incompatibility here?

One may want to understand these statements in the sense that modality unspecific systems are seen as necessary and modality-specific systems as optional. However, this does not seem to be sensible; it would obviously be wrong to state that the thrust pushing an airplane *occurs in* one of its three engines because two of them can optionally be switched off. There is reason to say that, if all three are at work, the airplane's thrust in fact *occurs in* all three of them – even though one alone may do the job. The statements about (i) the occurrence of understanding exclusively in the modality independent system and (ii) this system's dynamic interaction with action and perception mechanisms in meaning processing must both be understood as statements about system functionality. In this reading, there seems to be a conceptual issue, as these statements are indeed incompatible with each other. If "modality-independent" semantic areas and action/perception systems exchange the information they process, then the latter must receive *semantic* information from the former, be allowed to process, enrich and ground this information with/in information about actions and perceptions and *send the resultant enhanced semantic information back*. Crucially, as semantic information would, in this view, be processed both in modality-independent symbolic and in action–perception systems, it seems impossible to justify why, in such an architecture, understanding should "occur" only in the modality-independent semantic system. The interactivity statement *implies* that action/perception systems can provide a genuine locus of semantic processing – not necessarily for all symbols, but at least for some. Likewise, it is difficult to justify that semantic information would merely be "colored" or "dressed", rather than being fundamentally changed or *transduced* by the action–perception system. Functional interaction entails distributed cognitive processes and, in this specific case, semantics in action and perception systems. At least for words typically used to speak about objects and actions, it seems necessary to acknowledge a genuine semantic role of sensorimotor information and action and perception systems of the brain. This is precisely the sense in which Barsalou, Glenberg and several others postulated a contribution of sensorimotor brain and cognitive systems to semantics and concepts (Barsalou, 1999; Glenberg & Kaschak, 2002; Pulver-

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[5] On the empirical side, Mahon and Caramazza emphasize dissociations between understanding and acting in neuropsychological patients, for example between the abilities to imitate pantomimes and to produce and comprehend the corresponding action verbs, as well as between the ability to use tools and the ability to comprehend the corresponding tool nouns (see, for example, Papeo, Negri, Zadini, & Rumiati, 2010). But these and similar dissociations do not constitute any difficulty for an account viewing articulatory, acoustic and semantic representations of a word as tied together by distributed neuronal circuits (see Sections 3 and 4.4, and also Plaut & Shallice, 1993; Pulvermüller & Preissl, 1991). Not only will lesions at different loci within a distributed representation have dissociating effects, it should also be clear that the different tasks involve additional cognitive and perceptual processes to different degrees, which may lead to additional dissociation. For example, the visual-perceptual abilities required for exact imitation of pantomime or for grasping an object are quite different from those required for typical linguistic tasks. Note, furthermore, that even within the domain of acting upon objects there are fine-grained dissociations that are best attributed to differential processing of perceptual parameters relevant for action in dorsal and ventral visual streams (Goodale, Milner, Jakobson, & Carey, 1991; Jeannerod, Arbib, Rizzolatti, & Sakata, 1995; Milner & Goodale, 2008).

müller, 1999).[6] Unfortunately, although Caramazza and his colleagues seem to realize that interactivity is required, their modality-independence statement about understanding, which may be inherited from the tradition of modularism, appears incompatible with this insight. If they make the necessary inferential step from interactivity to distributed semantics, their model will be in line with current embodied or grounded perspectives (Barsalou, 2008; Glenberg & Gallese, 2012; Kiefer & Pulvermüller, 2012; Pulvermüller, 2012).

In essence, we are now very close to seeing language, perception, and action systems as nonmodular and dynamically-interactive, which implies distributed semantics also involving action and perception systems (for specific semantic types of words and constructions).

2.4. Why grounding is necessary for semantics and a symbolic "amodal" system is not sufficient

According to disembodied theories of meaning, the mechanisms of perception and comprehension of signs are distinct and functionally separated from those of relating these signs to objects in the world or to actions the subject could potentially engage in. Similarly, minimally-embodied proposals such as those made by Caramazza's group place concepts and meaning in an amodal (modality-unspecific) symbolic system, with optional "dressing" contributions of action and perception systems. These approaches will now be considered in light of semantic theories.

Semantic theories view knowledge of the referent object(s) of a word as *an integral part of* its meaning (Frege, 1980; Quine, 1960). This is not to say that meaning can be reductively construed as reference; clearly, other well-known meaning facets need to be covered over and above reference (Chierchia & McConnell-Ginet, 2000). In analytical philosophy, language is considered to *receive its meaning from* the embedding of signs into typical contexts of actions and interactions between individuals who speak the language (meaning as use, Baker & Hacker, 2009; Wittgenstein, 1953). In the context of semantic theories of reference and use, a functional separation of referential semantics and action semantics from abstract "amodal" semantics seems inappropriate, because one is constitutive for the other. Knowing the meaning of a word or construction requires and includes the ability to identify entities which the utterance is used to speak about. The intrinsic link between perception, action and semantics/concepts is bolstered, for example, by evidence from deprived populations. For example, color concepts and resultant semantic categorization in congenitally blind people differ from those in people to whom this referential visual knowledge is available (see, for example, Connolly, Gleitman, & Thompson-Schill, 2007).

Still, respectable psychological theories of meaning have framed semantics in terms of relationships between signs, so that the meaning of one sign is characterized by the other signs it co-occurs with or relates to (e.g., Collins & Loftus, 1975; Landauer & Dumais, 1997). In such an approach, referential links or action connections are not part of the semantic system *per se*. and it may seem to make sense to functionally dissect semantics from action and perception systems in a "disembodied" or modular fashion. However, it is necessary to realize that such a symbolic semantic system misses an important component of semantics, the crucial relationship of signs to objects and actions (Glenberg & Robertson, 2000; Harnad, 1990; Searle, 1980). In his "Chinese room" example, Searle had shown that a person who has learned to manipulate and combine the symbols of a foreign language with each other flawlessly, yet without knowing their object, action, or life relationships, cannot be said to know or understand the meaning of that language, or to use it meaningfully. This paradigm shows that semantics is more than recombining symbols. One may argue that "there is nothing more physiologically or logically real about perception than about abstract cognition" (Landauer, 1999), but, within a functional semantic system, "word–word" combinatorial knowledge needs to be complemented by semantic information about "word–world" relationships (Cangelosi, Greco, & Harnad, 2002; Pulvermüller, 2002a). Any symbolic system requires reference and semantic grounding of meaning in the world and in interaction. For a language to convey meaning, it needs at least some words and constructions that can link up with objects, their sensorimotor features and actions. A symbolic system in itself cannot achieve this. We need to know what we speak about in order to speak meaningfully.

An argument similar to that made above for single signs and words can be made for whole sentences: Construing sentence meaning as an abstract symbolic process likewise faces important theoretical counter-arguments rooted in semantic theory. For a large class of the uses of the word "meaning", the meaning of this word can be explained as the truth conditions of an assertive sentence or statement (Chierchia & McConnell-Ginet, 2000; Davidson, 1967; Frege, 1980). Now, a disembodied account, and equally the minimally-embodied ones discussed above, can explain the meaning of sentence (S1) but not (S2).

(S1) A bear has fur.
(S2) This bear has fur.

Assessing the truth of sentence (S1), and therefore part of its meaning (Frege, 1980), is possible by relating the semantic concepts of BEAR and FUR to each other. As a bear is, by definition, a mammal and mammals are (at least in the vast majority of cases) hairy creatures, a general statement expressed by (S1) can be judged as (almost) universally correct. Such judgment is possible within an "amodal", even encapsulated (lexico-) semantic system relating semantic concepts to each other. However, the phrase "this bear" in (S2) is typically used to refer to one specific bear, and it could be one whose fur has just been shaved off. To judge the truth conditions of the assertion that (S2) is correct, it is, in many cases, not sufficient to consider the semantic relationship between linguistic expressions. If (S2) is used to speak about a real bear (e.g., while the speaker points to it when using the deictic particle "this"), and one were to judge whether (S2) is correct, it would be necessary for one's linguistic system to make contact with perceptual systems. If one were to believe in the existence of an amodal semantic system, one had to acknowledge that *processing and judging the meaning of assertion (S2) requires processes in the "interface system" connecting the hypothetical amodal semantic system with the perceptual system*. In the context of empirical statements about the world, an amodal semantic system is insufficient for processing meaning. There can be semantics in the perceptual interface. And, by extension, in the action interface too.

These statements can be reformulated as statements about the neurobiological level: If we assume that there are two distinct neuronal representations – one for the sentence and proposition "that this bear has fur" and one for the perception of an entity that is indeed a hairy bear – the verification of the statement requires the activation of both representations, plus a priming-type relationship between the two so that the semantic link is implemented. This consideration provides one more argument that a semantic theory confined to an amodal system cannot be a full semantic the-

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[6] There is, by the way, no escape line from this argument using the processing/representation distinction, proposing that the processing may be interactive but the semantic representations still limited to the "modality-independent" semantic system. This is because the performance of the semantic transduction processes requires the availability of the transducer, whose mechanisms are of course open to a description in terms of symbolic formulae.

ory. A full semantic theory needs to cover information about perception and action.

One more inadequate assumption, which has been haunting the discussions about embodiment, should be addressed: the idea that concepts are always the same, or at least share a common kernel, whenever they are applied. Mahon and Caramazza conclude that, since dogs come with different perceptual features, the DOG-concept, which, in their view, must be the same in different contexts (and at different times, in different people) cannot have perceptual features as constitutive parts (p. 68, Mahon & Caramazza, 2008). Also in this context, a brief look at semantic theory is helpful: What is the concept of a GAME? As games can be so extremely different from each other (consider chess, football, solitaire, and Counter-Strike), it is impossible to define the set of games by a set of shared semantic features (Baker & Hacker, 2009; Wittgenstein, 1953). The union of semantic features of all games would certainly result in a set which is not sufficient for uniquely defining the concept. So, indeed, concepts and word meanings depend on context and the different context-dependent word meanings resemble each other like the members of a family, with some members sharing features but others being entirely different. This well-known fact led semanticists to adopt the term "family resemblance" to describe the relationships between the different meaning-facets of words such as "game", "justice", "dog", or "bear" (see Barsalou, 1982; Kiefer & Pulvermüller, 2012; Rosch & Mervis, 1975; Wittgenstein, 1953). Thus, context-independence of concepts cannot be used to justify an amodal semantic system because such context-independence is illusory. A more flexible neurosemantic model is necessary (for elaboration, see Pulvermüller, 2002b).

In sum, essential components of meaning, including processing of reference and of truth of certain empirical statements, cannot be realized without involvement of perception and action systems. Information about action and perception provides important criteria for the semantically appropriate application of concrete words and constructions and for that of abstract utterances too. The intuition that a word always means the same thing, and a concept is always the same, regardless of its context, does not quite stand up to scrutiny; the context-relationship of sensorimotor semantic features is therefore not more surprising than that of other semantic features. Therefore, semantic theory appears consistent with a role of action and perception information in meaning processing.

2.5. Learning abstract word meaning

Arguments for semantic grounding in action and perception are usually made for concrete words and statements used to speak about actions and objects. Therefore, it has been speculated that a grounded or "embodied" approach might generally be insufficient for *abstract concepts* and that only an amodal symbolic system can "account" for them (Mahon & Caramazza, 2008). However, exactly the same points made in the context of reference above apply to abstract concepts and meanings too.[7] Wittgenstein suggests that (the) meaning (of a word or construction) is what the explanation of (this) meaning explains (§560, Wittgenstein, 1953). So how would we explain the meaning of "justice", say to a child? Typically by mentioning situations that can be taken as instantiations of JUSTICE – children receiving each the same amount of sweets, a thief having to pay for stolen goods, a killer being locked away for life for his killings. The situation-embedding of abstract conceptual knowledge can be traced experimentally (Barsalou & Wiemer-Hastings, 2005). Although a collection of exemplars cannot, of course, account for generalization of the concept, each and every typical exemplar can provide a basis of generalization to similar cases. Crucially, without concrete examples of situational instantiations, or *action–perception manifestations*, it is hard to see how an abstract meaning or concept could be introduced to a language learner lacking similar concepts in the first place. Dictionary definitions – Webster's explains JUSTICE as "The quality of being just or fair" – and feature list models – which may "explain" the meaning of JUSTICE by a semantic feature [+ just] – use a partially circular strategy in explaining novel abstract meaning, which does not appear to be particularly helpful in the explanation process. Thus, there seems to be no alternative to listing typical examples (that is, action–perception manifestations) if one were to explain the meaning of abstract words to a first-language-learning child.[8] Furthermore, as abstract concepts such as JUSTICE are highly culture-specific and subject to change over time, the possibility of inborn ideas does not seem to provide a fruitful explanatory avenue in this and similar contexts either.

Vigliocco and colleagues have pointed to a connection between abstractness and emotional–affective meaning. Many (although not all) abstract words are rated as highly emotional (or "arousing") in meaning (Kousta, Vigliocco, Vinson, Andrews, & Del Campo, 2011). Therefore, explaining the semantics of abstract words used to speak about internal states and emotions may be particularly relevant for understanding abstract semantics generally. If these words receive their meaning, in part, through grounding in emotion, it still needs to be explained how this emotion grounding can be established, which an amodal semantic system account does not address. Assume the amodal semantic system contains an inborn emotional concept of STINGINESS; how could a learner know to relate it to the corresponding word, and not to "lavishness"? The classic answer in semantic theory is that this is possible, because the abstract emotion concepts have characteristic ways in which they are *manifest in behavior, in the actions and interactions the learner engages in with speakers of the language* (Wittgenstein, 1953). So the link between an abstract emotion word and its abstract concept is by way of the manifestation of the latter in prototypical actions. The child could be taught an abstract emotion word such as "joy", because it shows JOY-expressing action schemas, which language teaching adults use as criteria for correct application of the emotion word "joy". Thus, the motor manifestation of the emotion becomes the crucial link between word use and internal state and, hence, between sign and concept. This proposal predicts that abstract emotion words do not only activate limbic emotion-related circuits but, in addition, the motor system controlling face and arm actions with which emotions are typically expressed. Such motor involvement in abstract emotion word processing can be predicted for language learning children and, if the "embodied" motor link persists throughout later life, in adults as well. Motor system activation for emotion-expressing body parts was indeed found when adults passively processed abstract emotion words (Moseley, Carota, Hauk, Mohr, & Pulvermüller, 2012), suggesting that for one important class of abstract concepts grounding in action is of the essence. For other abstract words and constructions, neuroimaging results suggest different cortical correlates in both modality-specific and multimodal areas (see, for example, Binder, Westbury, McKiernan, Possing, & Medler, 2005; Boulenger, Hauk, & Pulvermüller, 2009; Fiebach & Friederici, 2004).

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[7] Some cognitive scientists do not distinguish between meanings and concepts, treating these terms as more or less equivalent. In semantic theory, a distinction is usually made between them: whereas concepts may exist independently of language, meanings are concepts with an intrinsic link to individual signs, so that these "semantic concepts" are manifest in the use of the sign. Here I focus on meaning assuming that any conclusions apply to other concepts too.

[8] This does not explain how one unique abstract concept of JUSTICE could emerge from the variable examples; but such an explanation is nonessential as the "unique abstract concept" may not exist (see family resemblance argument above).

2.6. Confusions about double dissociations

There is an ongoing debate about the status of double dissociations in neuropsychological research which recently spilled over in the embodiment debate. Mahon and Caramazza have argued that "if two representations (e.g., the concept HAMMER and the motor information about how to use hammers) are represented over the same sets of nodes in a network, then they cannot strongly dissociate" (Mahon & Caramazza, 2008). Contrasting with this view, Shallice has argued that lesions affecting the incoming and outgoing ends of one central distributed representation may primarily cause dysfunction in one modality (Shallice, 1988); numerous network simulation studies further demonstrate double dissociations in systems with distributed representations (e.g., Garagnani, Wennekers, & Pulvermüller, 2008; Plaut & Shallice, 1993; Pulvermüller & Preissl, 1991). Note again the example of interacting action and "modality-independent" systems: Even if the latter is said to provide proper semantic feature integration while the former is just attributed a "dressing" role in such processing, a lesion of either part of any truly *distributed semantic system* including both multimodal and action parts will have its very specific and dissociable effects on semantic processing.

If action and perception representations are bound together in distributed action–perception circuits, or APCs (see Section 3 for further explanation), the feedback and feedforward flow of activation in these APCs will enhance processing and any significant lesion on either the motor or the sensory side will have an impact of processing efficacy on the other. Still, a relatively more pronounced motor deficit will result from lesion on the motor side of the APC, whereas a perceptual deficit will dominate with lesion at the sensory end (e.g., Pulvermüller & Preissl, 1991). The same argument applies to other double dissociations too, e.g. between phonological and semantic deficits in aphasia or between object use and recognition in apraxia and agnosia (Negri et al., 2007; Papeo et al., 2010). Double dissociations are therefore consistent with models building on intrinsic linkage of action and perception mechanisms (see Section 3), and with grounded or embodied models building upon such action–perception links.

2.7. Multiple semantics: necessary for avoiding multiple confusions

Semantic models rooted in action and perception postulate multiple modality-specific semantic systems in motor, somatosensory, gustatory, olfactory, auditory and visual systems (e.g., Kiefer & Pulvermüller, 2012; Pulvermüller, 1999; Shallice, 1988, 1989; Warrington & Shallice, 1984). As there are words like "walk", which are used to speak about one type of action, and words like "groundhog" referring to objects with specific visual features, it has been suggested that the brain devices for such "action" and "visually-related" words are neuronal assemblies linking a word form or symbolic network part in perisylvian frontal, parietal and temporal cortex *especially strongly* with action or object knowledge stored in motor or visual systems, respectively (Section 3.2, see Kiefer & Spitzer, 2001). However, concrete words (including "walk" and "groundhog") typically not only relate to knowledge from one modality. A TROUT has a specific fishy look, touch, taste and possibly smell, and one may even know how to catch one. How would these pieces of knowledge, supposedly stored in different sensory and motor systems, be integrated with each other? A famous argument was that such integration of multimodal semantic information requires one single amodal semantic system, where all information comes together (Patterson, Nestor, & Rogers, 2007), or, alternatively, reduplication of all semantic knowledge in each of the modality-specific systems (Caramazza, Hillis, Rapp, & Romani, 1990). Caramazza et al. argued that, in this latter view, "it is not possible to have a coherent theory of multiple semantics that distinguishes between different semantic systems on the basis of format of representation and at the same time includes within any format-specific system the disparate sorts of information" (Caramazza et al., 1990). Is this reservation motivated against modern models of category-specific semantics and, by extension, against semantic grounding and "embodiment"?

The model of semantic circuits summarized below in Section 3 removes the problems seen by Caramazza et al. by distinguishing between semantic systems on one side and semantic circuits on the other.[9] Modality-specific semantic *systems* are sets of brain *areas*. In contrast, semantic information is integrated by individual semantic *representations* neurobiologically realized as distributed neuronal *circuits* binding specific information about action and perception. Critically, these circuits are typically distributed over a range of modality-specific and multimodal cortical areas. Therefore, the circuits – and not the areas – provide the mechanism for semantic/conceptual information integration across modalities (Pulvermüller, 1999, 2012). The distribution of these circuits over specific cortical areas – including motor, visual and other modality-specific as well as multimodal cortices, with especially strong connections among neurons processing semantic features of special relevance – does not pose a "multiple-representation problem", as suggested by Caramazza et al. (1990) in their discussion with Shallice (1988, 1989). At the cognitive, psychological and linguistic levels, the distributed circuit is best described as *one single multimodal semantic representation with specific distribution over a set of cortical areas*. Here, the crucial insight is that the local area is not the only candidate information processor, but that the *distributed circuit (or cell assembly) may act as the unit of information integration* (Fuster, 2003; Hebb, 1949; Milner, 1996; Palm, 1982; Pulvermüller, 1996). Again, the cell assembly or distributed representation can reach into modality-specific systems and into multimodal ones too.

In fact, the assumption of multiple semantic systems is necessary to explain the huge body of evidence about category-specific semantic deficits (Section 4.4). The notion of trans-area semantic circuits as integration devices with differential connectivity into category-specific semantic systems is compatible with additional areas generally contributing to semantics, either in the sense of a "semantic hub" or in that of a "power plug" for conceptual and semantic processing (Patterson et al., 2007; Pulvermüller & Schumann, 1994). The across-the-board semantic deficit seen in semantic dementia provides evidence that the anterior temporal lobe and underlying subcortical structures, including the amygdalae, which are damaged in semantic dementia, may provide such a multimodal semantic site (Patterson et al., 2007). Note, however, that there is a degree of semantic category-specificity in Semantic Dementia (Gainotti, 2012; Pulvermüller et al., 2010) and that profound bilateral inferior- and anterior-temporal damage caused by herpes simplex encephalitis sometimes leads to clear category-specific semantic deficits (Warrington & Shallice, 1984), thus raising questions about a temporal semantic area treating all word types alike. (Pulvermüller, 2013). ((*Trends in Cognitive Sciences, in press*)).

2.8. Summary

This section clarified some misrepresentations which somewhat encroach the embodiment debate. (1) Embodied theories do not construe semantics reductively in terms of motor and sen-

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[9] The distinction between structural system (region, area) and functional circuit (cell assembly) is missing, for example, in Shallice's paper from 1989, where he suggests that "the semantic *system* is a large distributed *network* within which more specialised sub*regions* have developed; this might arise because it is a system which receives many types of input at different entry points and serves a number of different systems from different exit points" (p. 141, Shallice, 1989).

sory information. (2) Action perception representations do not merely have a non-constitutive "dressing" or "coloring" role in conceptual-semantic processing; this minimally-embodied view is difficult to reconcile with causal effects of action systems on semantically-specific processes. (3) Functional interaction between action, perception and multimodal systems implies that if one of these systems processes meaning, the others do so too. (4) Meaning processing without reference is incomplete; symbol grounding is necessary for semantics. (5) Abstract words, like concrete ones, need to be explained and grounded in the context of concrete actions and perceptions; otherwise semantic learning is difficult to achieve. In addition, (6) common double dissociations between perception and action are consistent with embodied distributed circuits, which (7) can act as integration devices for multimodal semantic information. Therefore, previous criticisms of embodied approaches (Sections 2.1, 2.5–2.7) cannot be maintained and alternative minimally-embodied proposals are insufficient (Sections 2.2–2.4).

3. Action–perception theory (APT) of semantic circuits

In my view, the question of whether models of cognition should be embodied or disembodied is secondary. The primary question in cognitive science, and, at the same time, one of the most exciting issues in neuroscience, addresses the *mechanisms* of cognition. These mechanisms are brain mechanisms. One can formulate the answers in terms of box-and-arrow diagrams (Caramazza & Coltheart, 2006) or precise algorithms implemented as abstract automata (Chomsky, 1963), but it appears to represent an advance to spell out the critical mechanisms in terms of neuronal automata and circuit dynamics (Buzsáki, 2010; Pulvermüller, 2010).[10] In this sense *brain-embodiment* is at stake in brain science and in cognitive science too (Patterson & Plaut, 2009; Plaut & Patterson, 2010). In the context of the embodiment debate, the to-be-investigated claim therefore is that, within a neurobiological model of semantics (which is a cognitive model with a biological basis), it is fruitful and necessary to incorporate action and perception systems of the brain and mind in the context of an action perception theory (APT).

3.1. Storing word forms by linking action to perception

Action–perception theories have been offered as a foundation of language mechanisms in general, and semantics specifically (Allport, 1985; Braitenberg & Pulvermüller, 1992; Damasio, 1989; Farah & McClelland, 1991; Fuster, 2003; Humphreys & Forde, 2001; Mesulam, 1998; Pulvermüller, 1999; Shallice, 1988; Warrington & McCarthy, 1987). A principal idea is that correlated activity in sensory and motor brain systems, especially in the cortex, and pre-existing neuroanatomical connections drive the formation of major building blocks of cognition, language and meaning. Such sensorimotor correlation leads to the formation of functional units, called neuronal assemblies or *action perception circuits (APC)*, with specific functional properties (e.g., Braitenberg, 1978; Braitenberg & Schüz, 1998; Buzsáki, 2010; Palm, 1982; Pulvermüller, 2002b; Sommer & Wennekers, 2003). An APC has strong internal connections, and therefore its partial activation will eventually ignite the circuit (providing a mechanism for recognition), although individual ignitions may differ from each other depending on context and the previous activity state of the network. Upon ignition, APCs may retain activity for some time (working memory). To control activity, the system requires a cybernetic regulation mechanism (Braitenberg, 1978; Palm, 1982; Sommer & Wennekers, 2003), which includes inhibition between circuits and prevents several APCs from igniting at a time. Such regulation provides a putative mechanism for lexical competition and attention (Garagnani et al., 2008). Different APCs may overlap (modeling, for example, phonologically or semantically similar words, along with ambiguous words, Pulvermüller, 2002b). That action and perception mechanisms are indeed interlinked is demonstrated by a range of neuroscience facts, especially the existence of mirror neurons in premotor and parietal cortex carrying motor and sensory, and sometimes even higher, goal-defining functions (Arbib, 2005; Fogassi et al., 2005; Rizzolatti & Arbib, 1998; Rizzolatti & Craighero, 2004; Rizzolatti, Fadiga, Gallese, & Fogassi, 1996; Rizzolatti & Sinigaglia, 2010).

Anatomically, primary motor and sensory auditory and visual areas are not interlinked directly but by way of other areas, including "higher" motor and sensory as well as multimodal areas not dedicated to one specific sensorimotor system. Specific reciprocal next-neighbor and long-distance connections provide between-area connections. Note that this connection structure contains abundant information, which is, to a great extent, determined by the genetic code. Due to learning, sensory and motor circuits become linked with each other, for example when the child uses syllables and spoken words and therefore connects motor with sensory information about speech (Fig. 1a and b). The mechanisms of sensorimotor linkage, which can be tracked neurophysiologically in the language learner (Pulvermüller, Kiff, & Shtyrov, 2012), is analogous to the well-known mirror neuron mechanisms documented in monkeys and probably present in humans too (Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995; Rizzolatti & Sinigaglia, 2010). Consistent with this view, motor and premotor cortex activation reflects speech sound perception (Fadiga, Craighero, Buccino, & Rizzolatti, 2002; Pulvermüller et al., 2006) and functional changes in the motor system influences the perceptual classification of speech sounds (D'Ausilio et al., 2009).

Basic APCs and mirror mechanisms can transform perceptual patterns into motor acts, thus supporting repetition, mimicry, mirroring or uncontrolled contagious yawning (Fig. 1a and b). To model social interaction and language, additional mechanisms are necessary that link linguistic actions into sequences and words and larger constructions to meaning (Fig. 1c and d, Arbib, 2010; Jacob & Jeannerod, 2005; Jeannerod, 2006).

Crucially, the mechanisms of interlinking action and perception representations has been investigating by neurocomputational simulation studies, which help to put "embodied" language models on solid mechanistic ground (see, for example, Arbib, 2010; Bonaiuto, Rosta, & Arbib, 2005; Madden, Hoen, & Dominey, 2010; Westermann & Reck Miranda, 2004). In recent computer simulations of the underlying neuromechanistic processes, we used neural networks mimicking the neuroanatomy of the left-perisylvian language cortex to investigate, at the neurocomputational level, the formation of action–perception circuits for spoken word forms (Garagnani et al., 2008; Wennekers et al., 2006). The neurocomputational model realized important features of neuroanatomical connectivity, especially connections between primary motor and auditory areas by way of inferior-frontal premotor and prefrontal and superior–temporal auditory parabelt and belt areas (Glasser & Rilling, 2008; Petrides & Pandya, 2009; Saur et al., 2008).[11] Cor-

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[10] Why should this be an advance? Because for understanding and repairing a device, it is best to speak about its parts and their mechanistic interactions. A box–arrow diagram is good, but a plot of gear box and con-rod is better.

[11] As rich connections link both posterior temporal (dorsal) as well as anterior and inferior temporal (ventral) areas to prefrontal and premotor sites, the model realises the same action–perception links for phonological and lexical processing in both dorsal and ventral connection pathways. There is, in fact, no neuroscientific *a priori* why only the dorsal pathway should specialise in phonological or lexical processing (see Dewitt & Rauschecker, 2012; Pulvermüller et al., 2006; Uppenkamp, Johnsrude, Norris, Marslen-Wilson, & Patterson, 2006).

related activity in the model's motor and sensory areas (simulating processes of speaking and simultaneously hearing a word) yielded coordinated waves of activation travelling through this network architecture. Due to realistic Hebbian learning mechanisms, the correlated inter-area patterns of activation led to synaptic strengthening and neuronal circuit formation. Consequently, the resultant circuits included neurons in sensory and motor areas but, in addition, neurons in areas through which connections between sensory and motor areas are being relayed, including, for example, multimodal inferior-prefrontal and auditory parabelt areas. Thus, neuroanatomy provided the necessary substrate, learning strengthened the links, and the results were multimodal circuits connecting motor and sensory neurons by way of other neurons in a range of supra- and multimodal *relay areas* (premotor, prefrontal, parabelt and belt). Note that because partaking neurons are being integrated into action–perception circuits, APCs, they acquire multimodal response properties.

APCs provide a cortical basis of working memory (Fuster, 1995, 2003; Verduzco-Flores, Bodner, Ermentrout, Fuster, & Zhou, 2009; Zipser, Kehoe, Littlewort, & Fuster, 1993). Critically, neurons in relay areas are in the *center* of circuits bridging between sensory and motor cortices. Therefore, these relay area neurons receive "support" (i.e. neuronal activation) from both sensory and motor ends of the network. In contrast, neurons in the circuit *periphery* in the motor cortex or the auditory cortex would receive such within-assembly support only from one side, i.e., "top-down" from the higher areas. Because of their stronger neuronal support, neurons in the relay areas are able to retain activity long after stimulation, thus making them a substrate of working memory. Because of their weaker support, circuit neurons in sensorimotor areas play less of a role in working memory processes. These mechanistic considerations predict a process of *memory disembodiment*, which, within APCs, makes working memory processes move away from sensorimotor areas. As the most "central" parts of the circuits, in prefrontal and auditory parabelt, hold activity for the longest period of time, these sections of the circuits are most crucial for storing information about word forms that co-occur with each other, that is for the storage of combinatorial semantic information (Garagnani & Pulvermüller, 2013; Pulvermüller & Garagnani, submitted for publication). Note that this explains "disembodiment" in terms of neurobiological mechanisms.

3.2. Storing meaning by interlinking action–perception circuits

Syllables, word forms and verbal utterances do not stand alone. As they are embedded into context, their neuronal representations link up with other circuits. Two types of learning are most important, which have sometimes been called *word–word* and *word–world learning*, respectively.

3.2.1. Word–word correlation learning

The meaning of any word can be defined *combinatorially* by relating it to other words with which it typically occurs. Hence, word co-occurrence in strings and texts provides the crucial information extracted and systematized by combinatorial approaches to semantics (Kintsch & Mangalath, 2011; Landauer & Dumais, 1997). How would brains map such combinatorial information? Hebbian neuronal correlation learning algorithms (Artola & Singer, 1993; Caporale & Dan, 2008)[12] can map which words frequently occur together and which do not (Pulvermüller, 2002a). Words that frequently co-occur would therefore be bound together into sequences (Fig. 1c, Pulvermüller & Knoblauch, 2009). So, trivially, probability mapping stores the probability of symbol chains. However, we found in simulation studies with associative networks replicating certain aspects of cortical neuroanatomy, that, over and above probability mapping, the frequent mutual substitutions between syntactic constituents in similar syntactic–semantic contexts leads to the formation of *discrete combinatorial neuronal assemblies* now storing sequences at rather abstract levels, as sequences of classes of lexical items or construction schemas. Therefore, purely based on the combinatorial information about their frequent occurrence in noun-contexts, verbs can be grouped together, and, likewise, nouns group together based on their occurrence in similar contexts. Crucially, a general combinatorial link develops joining together the frequently recombined nouns and verbs (Knoblauch & Pulvermüller, 2005). This general link is the basis for *generalization* to novel combinations of lexical items. As mentioned in Section 3.1 above, linking areas in anterior-inferiorfrontal and auditory parabelt areas are best suited for storing semantic word–word correlations, because they house the majority of memory-active "core" neurons of APCs (Fig. 1c, Garagnani & Pulvermüller, 2013; Pulvermüller & Garagnani, submitted for publication). It indeed makes sense to speak of a mechanism of *combinatorial disembodiment* in this context.

Although such a combinatorial approach may be said to support combinatorial mechanisms at the syntactic level only, it is important to note that the networks in question also store and represent genuinely *semantic* information (Pulvermüller & Knoblauch, 2009). Closer analysis of combinatorial networks mapping noun-verb co-occurrence shows that semantic subgroups of thematically related nouns and verbs develop much stronger links than average nouns and verbs, so that combinatorial information mapped by the network is indeed both syntactic and semantic in nature. An action–perception theory with correlation mapping mechanisms in fact implies a combinatorial semantic system. Although it is composed of action–perception circuits the system stores combinatorial information and provides generalization at an abstract combinatorial-semantic level (Pulvermüller, 2010).

3.2.2. Word–world correlation learning

So far, semantic learning in a disembodied word–word correlation mapping sense has been addressed, thus still leaving the semantic grounding problem unsolved (Harnad, 1990; Searle, 1980). However, in a brain-like mechanistic device, such grounding is also implied by neuronal learning principles. If a word is typically used to speak about an object, the typical referent objects may frequently be present during word learning; the neuronal correlates of object and word would therefore be co-activated and, because of Hebbian learning, tighten their neuronal connections, thus forming a higher-order semantic circuit which binds together two kinds of action–perception circuits: that for the word form (or symbol) and that for the referent object (Fig. 1d). In this case, visual representations of referent objects in the middle and temporal lobe are of particular relevance. For sound-, taste- or odor-related words, neuron sets in auditory, gustatory and olfactory areas are implied. Circuits of neurons in different modality-specific systems linked by way of long-distance cortico-cortical connections bind multimodal semantic knowledge crossing sensory and motor modalities (FISH example in Section 2.4). That higher multimodal relay areas are involved, apart from modality specific ones (Fig. 1d), follows from the fact that neuronal connections between modality systems frequently switch over in specific higher association "relay" cortices or *convergence zones* (Damasio, 1989).

If a word is typically used to speak about one type of action, the prototypical word-related actions may frequently be performed – either by the learner him/herself or by a different individual. In this

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[12] Hebb-type correlation learning or probability mapping algorithms typically include synaptic strengthening when two connected neurons fire simultaneously ("fire together-wire together" rule) and "anti-Hebb" synaptic weakening when one of the neurons fires and the other is silent ("out of sync-delink" rule). In addition, the precise timing of pre-and postsynaptic spikes can also be taken into account. In all cases, probability of firing is mapped onto connection structure.

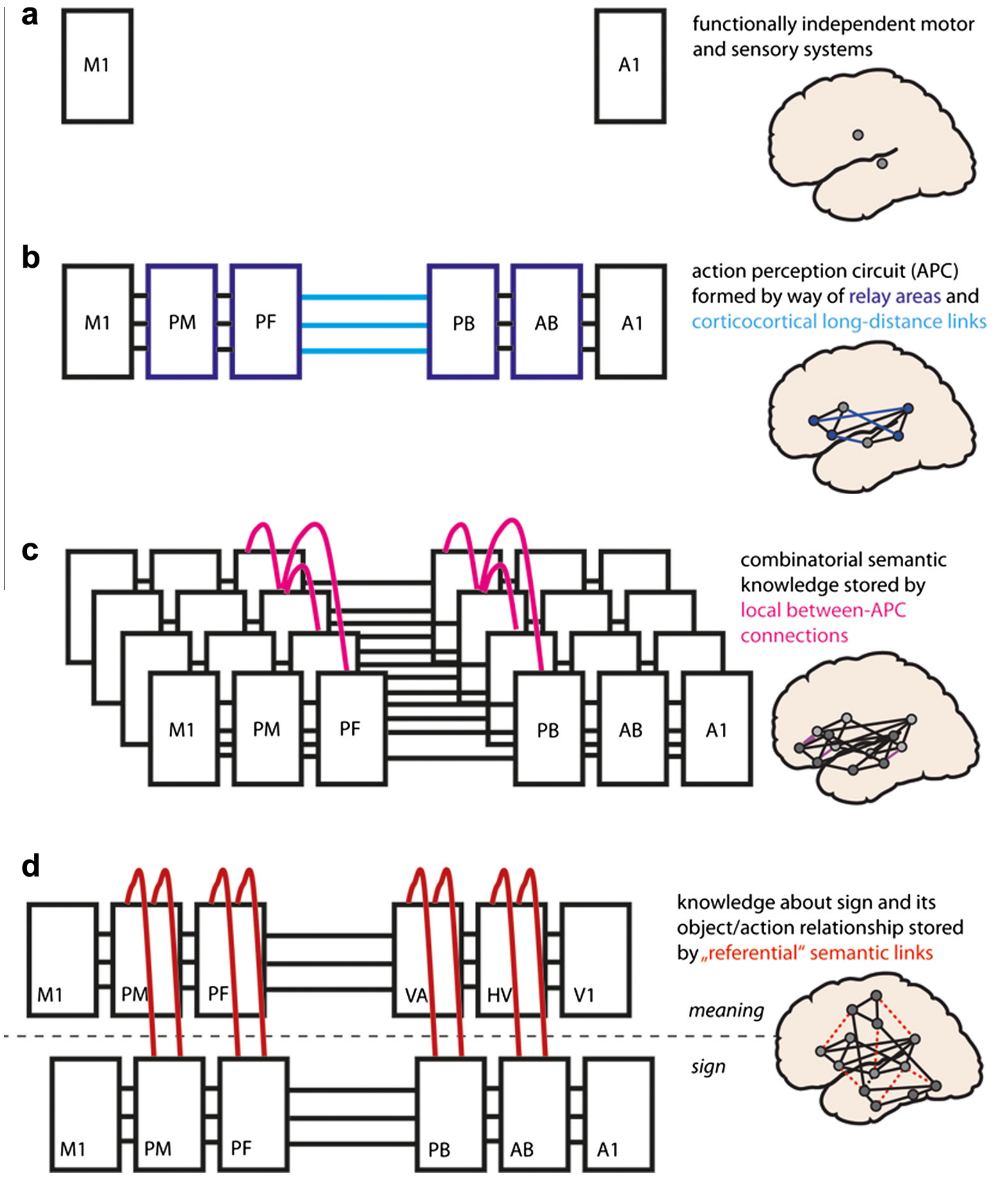

Fig. 1. Action perception circuits, APCs, and semantic mechanisms. (a) Modality-specific neuron sets in primary auditory and motor cortex (A1, M1). (b) Based on corticocortical connections and correlated activity patterns in motor and sensory areas, APCs develop for spoken word forms; these include neurons in primary areas and in *relay areas* bridging between them (inferior PM (premotor) and PF (prefrontal); superior–temporal AB (auditory belt) and PB (parabelt)). (c) Combinatorial semantic information is laid down by strengthening of links between PF and PB neurons of APCs, leading to storage of action chains and hierarchies. (d) Referential object-related and action information is semantically bound to words by way of long-distance links between APCs for word forms and concepts; the illustrated conceptual circuit involves neurons in lateral M1, PM and PF motor/executive cortex and in V1 (primary visual), HV (higher visual) and VA (visual association) cortex in the ventral object processing stream. Semantic links can be mediated by "abstract" logical circuits (Section 4.3).

case, co-activation of neuronal activity would be present in the symbolic, word-form related circuit and in that of the word-related motor schema. In this case, action representations join together with symbol circuits and potentially additional multimodal perceptual circuits. The motor schema circuits likely include neurons in the motor system of the human brain (Fig. 1d, Jeannerod et al., 1995).

Such a mechanism might be useful for binding meaning to words like "run" or "lick". If word-related actions are typically performed by humans (but not for nonhuman action, cf. "barking"), action knowledge will be tied into the semantic circuit. Action knowledge rarely exhausts the meaning of an action word, as there is typically additional semantic knowledge about executive and sensory aspects of the word-related actions, for example the visual properties of the action, knowledge about the possible objects the action can be performed on, its goals, and so on (Glenberg & Gallese, 2012; Pulvermüller & Fadiga, 2010).

There is an important difference between motor movements (also called "basic actions", Danto, 1965) and actions with a sometimes far-reaching goal (e.g., Fogassi et al., 2005). In action perception theory (APT), this difference is modeled by different types of action representations, either a single APC – the word form "jump", which connects the motor schema for a sequence of articulations with an acoustic–phonological perceptual schema – or a connected set of APCs including both the linguistic form, its semantic action or object-related schema and the representation of typical consequences (see also Glenberg & Gallese, 2012). So if somebody offers me crisps BY showing me the open bag and uttering the word "crisps?", the utterance's (basic action's) representation includes the word form circuit with its linked object representation (referential–semantic mechanism shown in Fig. 1d), but the wider action–semantic representation embeds this object representation into that of the expected action to be performed on the object and its verbal correlate (combinatorial semantic linkage mechanism, shown in Fig. 1c). Hence basic and goal-defined actions have separated interlinked mechanisms in this type of model.[13] Note, furthermore, that the serial and hierarchical linkage of action schemas (Fig. 1c) is also capable, in principle, of capturing sequences of actions performed by different individuals, for example the dialogue schema of a request being followed by the passing-on of the requested object by the dialogue partner and finally thanking (Egorova, Shtyrov, & Pulvermüller, submitted for publication; Pickering & Garrod, 2004). Developing a neurobiological theory of dialogue will be a prime target for the future.

A symbol-related APC will therefore "embody" a range of circuit parts storing action and perception schemas semantically related to a symbol. Whenever it ignites, the APC activates a selection of its semantic schemas, preferentially the most prototypical ones and those best primed by context. Within each circuit, the strength of connection (driven by correlation and thus typicality) and the priming status of the network before ignition determine on each occasion which circuit parts will partake in the ignition process. Note, once again, the importance of inhibitory mechanisms here, as for example in case of an ambiguous word form (such as "bank") only one of the alternative overlapping circuits will be allowed to ignite (Pulvermüller, 2002b).

3.2.3. Word–word plus word–world learning

As word–word and word–world correlation learning are specified mechanistically, it is important to consider the joint contribution of both to semantic learning. Words are frequently learned through context, without reference objects or relevant actions being present (Kintsch, 2008). Semantic learning by context does not only imply that word form representations are being joined together by combinatorial circuits, it also implies interaction between referential-semantic and word form circuits. Due to neuronal correlation, the word form circuit of the new to-be-learned word form (e.g. "unicorn") may link with (part of) the semantic circuits of a previously acquired words ("horse", "horn"), thus resulting in attachment of referential-semantic neurons to the new word's circuit (Pulvermüller, 2002a). In this view, semantic learning in context entails that semantic grounding of some words and concepts previously learned in action and object contexts exerts "grounding contagion" on other words and concepts of the vocabulary. Note that a process similar to imagery (or intentional simulation) might play a role here, whereby the listener actively thinks of a scene, action or object related to known language units when hearing a novel item. However, as an alternative, the involuntary process of semantic understanding of meaningful language may instantaneously activate semantically-related action or object representations that consequently become available for semantic grounding of novel symbols occurring in the same context. Combinatorially-grounded semantic learning or "grounding contagion" may play a role for the large set of vocabulary items learned from context, in the absence of referent objects or relevant actions (cf. "symbolic theft" or "parasitic" semantic learning, Cangelosi, Greco, & Harnad, 2000; Cangelosi et al., 2002; Pulvermüller, 2002a).

Correlation learning implies that, for words occurring in very variable object and action contexts, any links between the representations of word form and objects/actions remain weak (Pulvermüller, 1999). This is especially important for words and morphemes with primarily grammatical function, that is, grammatical function words and affixes. As they typically line up with words from specific grammatical categories, they are being joined into the combinatorial network, however without acquiring their own semantic links to perceptual or action schemes. The referential-semantic detachment of function words and affixes is a case of "disembodiment" and follows from neurobiological correlation learning.

3.2.4. Logical circuits for abstraction

For a relevant subclass of words, the sets of basic actions or objects they relate to are so heterogeneous and variable that searching for common features or a prototypical perceptual schema is a challenge. The famous example of "games" has been highlighted (Section 2.4). Consider furthermore the range of objects that can be called "beautiful", which may include flowers, faces and scenes such as a sunrise. Likewise, the actions one can perform to "free" somebody are equally heterogeneous: unlocking a door or removing handcuffs may do the job as does a sentence spoken by a judge. Searching for common features may work to a degree (e.g., by using the "out of a container" metaphor, Lakoff, 1987; Langacker, 1991), but there may still be need to store the knowledge that *a heterogeneous range of alternative objects or actions* fall under a given abstract concept. A neurobiological mechanism for realizing such *or*, or *either-or*, connections between object types and action schemas can be provided by *logical circuits*. Depending on its connections with other neurons and its activation threshold, a basic type of model neuron can be described as a logical unit calculating AND, OR, or EITHER-OR functions (Kleene, 1956; McCulloch & Pitts, 1943). A description in terms of logical conjunction and disjunction may not be fully appropriate for the functionality of individual neurons (as suggested by McCulloch and Pitts) but such a description has been discussed at the higher level of large neuronal assembly interaction (see, for example, Bussey, Saksida, & Murray, 2005; Hayon et al., 2005; Palm, 1982). Accordingly, several APCs converging on a target postsynaptic APC by way of *strong* connections may each be able to reliably ignite the latter, thus representing a probabilistic OR link or disjunction. If links are weak, several simultaneous inputs will be required to activate the postynaptic circuit, thus representing an AND link or conjunction. Disjunction links between APCs are especially handy for implementing, at the neuronal circuit level, the many-to-one relationship between action and perceptual instantiations of abstract meaning and the word form expressing such variable meaning in different contexts (Pulvermüller, 2008). Note that as OR or EITHER-OR circuits need to compute input from a range of APCs, the logical key circuits can be assumed to lie outside sensorimotor areas, in adjacent prefrontal and anterior-temporal areas where sensory and motor pathways converge (Fig. 2). A move of abstract semantic representations away from sensorimotor systems may therefore be driven by the great variability of action–perception instantiations of specific types of abstract concepts. The term *variability disembodiment* may be appropriate in this context. A resultant empirical prediction is that abstract word meanings will differ in their brain processing loci dependent on their variability of usages (see also Pulvermüller 2013).

3.3. Summary

A mechanistic model of word form and semantic processing is described briefly, with special emphasis on the integration of combinatorial and action–perception mechanisms. The following points are key to the embodiment debate: (1) The neurobiological mechanism of correlation learning implies semantic learning at the level of combinatorial word–word learning and at that of referential word–world learning, with significant interactions between the two. (2) Interlinked and overlapping APCs provide mechanisms

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[13] Some colleagues claimed incorrectly that action perception approaches, especially the mirror neuron theory, cannot account for the distinction between basic and goal-defined actions (e.g., Hickok, 2010; Mahon & Caramazza, 2008).

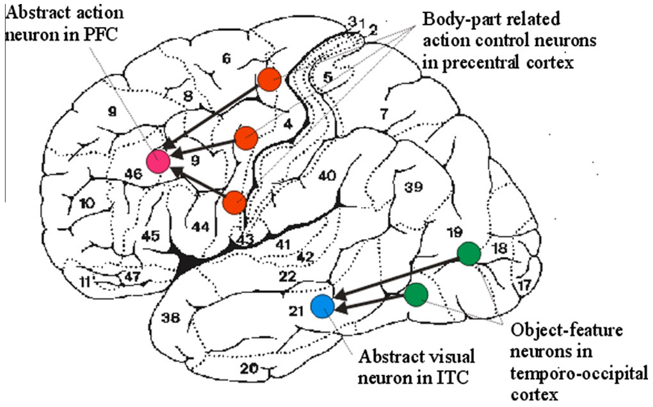

Fig. 2. Possible neuronal circuitry underlying modality specific semantic abstraction processes in the human brain. Abstract words that can be used to speak about a range of profoundly different actions (e.g., "to free") have cell assemblies including semantic neurons that act as disjunction units with input from a range of neurons controlling specific types of context-embedded body-related actions which are possible instantiations of freeing (to open a door, to unlock handcuffs, to ransom). Such abstract action–semantic neurons are located in prefrontal cortex. Similar abstract visual semantic neurons performing disjunction computations on visual object representations are in anterior areas of the inferior temporal "what" stream of visual processing; these implement the computation of visually-grounded abstract meaning (e.g., for "beauty" its instantiations as beautiful sunset, flower, face).

for sequences and hierarchies of words, actions and concepts. (3) Neurobiological mechanisms that are combinatorial and logical in nature are available for representing variable abstract concepts. In this context, mechanisms of "disembodiment" – defined as movement of critical processes away from sensorimotor systems towards multimodal association cortex – are explained by (a) memory dynamics, (b) combinatorial processes (which require memory) and (c) variability of word usage. Thus, although all semantic processes are grounded in action and perception, only a subset remain "embodied" in action and perception processes, with memory, symbol combination and variability of usage driving "disembodiment". A key feature of the action perception approach is its explanatory character, i.e. that it aims to derive and explain mechanisms and localizations from established neuroanatomical and neurophysiological principles and knowledge.

4. Some evidence relevant to the embodiment debate

4.1. Activation of sensorimotor systems in semantic processing

A range of studies showed that, for specific types of words and sentences, semantically-related local activation is present in perceptual and action-related systems of the brain (Binder & Desai, 2011; Kemmerer & Gonzalez-Castillo, 2010; Kiefer & Pulvermüller, 2012; Pulvermüller & Fadiga, 2010). The visual system becomes active when subjects passively read visually-related words and, more specifically, different areas in ventral temporal cortex are engaged when subjects understand words denoting color and form, faces and places, or visually-perceived movement (e.g., Aziz-Zadeh et al., 2008; Pulvermüller & Hauk, 2006; Rueschemeyer, Glenberg, Kaschak, Mueller, & Friederici, 2010; Simmons et al., 2007). Words semantically related to sounds ("bell", Kiefer, Sim, Herrnberger, Grothe, & Hoenig, 2008; Kiefer et al., 2012), odor ("cinnamon", Gonzalez et al., 2006) or taste ("salt", Barrós-Loscertales et al., 2012) activate their respective modality-specific perceptual areas. Also, activation of motor systems during processing of language semantically related to action knowledge has been demonstrated in a range of studies. Of special relevance is the finding of *"semantic somatotopy*", the activation of motor and premotor cortex according to the body-related action meaning of language. Many actions are typically performed with different parts of the body. KICKING, PICKING or LICKING are actions normally involving the legs, hands or tongue. This is not to say that there might not be exceptions, non-prototypical usages of these words: "kicking" in table football is certainly a hand/arm activity and one may sometimes "speak" by moving the hands, or "write" with one's foot in the sand. Therefore, not any, but the *prototypical meaning* (see, Rosch & Mervis, 1975) of words such as "kick", "pick" and "lick", and equally "walk", "write", and "talk", has a body-part implication, and semantic ratings of native speakers bolster this claim (Pulvermüller, Hummel, & Härle, 2001). As mentioned, the body part implication does not exhaust the semantics of these terms, as, for example, "walk", "stroll" and "march" have the same body part implication but relate to different (sets of) motor schemas. However, the specific significance of semantic somatotopy comes from the fact that theoretical neurobiological consideration for the first time allowed for specifying the loci of specific semantic brain activations, so that motor localizer tasks in which subjects did in fact move parts of their body, for example a finger or a foot, could be used to *a priori* predict semantic activation.

If the action a word, phrase or sentence is typically used to speak about is performed by moving the face, arms or legs, comprehension of these linguistic units will activate the concordant part of the motor system. The word "kick" would therefore activate foot/leg motor regions and "grasp" hand/arm regions. A range of studies found such somatotopic semantic mapping (for example, Aziz-Zadeh, Wilson, Rizzolatti, & Iacoboni, 2006; Boulenger et al., 2009; Hauk, Johnsrude, & Pulvermüller, 2004; Kemmerer, Castillo, Talavage, Patterson, & Wiley, 2008; Raposo, Moss, Stamatakis, & Tyler, 2009; Tettamanti et al., 2005; Tomasino, Werner, Weiss, & Fink, 2007). The specific significance of semantic somatotopy comes from the fact that neurobiological theory of language for the first time allowed for specifying the loci of specific semantic brain activations, so that motor localizer tasks in which subjects did in fact move parts of their body, for example a finger or a foot, could be used to a priori predict semantic activation. Therefore, for the first time, a brain locus of facets of semantics could be predicted correctly *a priori* with a degree of precision. Together with other evidence (González et al., 2006; Kiefer et al., 2008; Simmons et al., 2007), this finding provided unprecedented support for theories of category-specific semantic processing in the brain (Barsalou, 2008; Kiefer & Pulvermüller, 2012; Pulvermüller, 2005). Predictions are not precise in a millimeter sense but there seems to be significant spatial overlap of motor-related and word-elicited activations (Hauk et al., 2004). Somatotopic semantic mappings have been reported for sentences, phrases and verbs, in English, French, Italian, German, and Finnish. More recently, a degree of somatotopic activation in the motor system has also been found for nouns related to objects that respectively afford mouth and hand movements, that is, food and tool names (Carota, Moseley, & Pulvermüller, 2012). Strength and/or location of activity in frontoparietal sensorimotor systems varies according to other aspects of word meaning too, (Kemmerer et al., 2008; Rueschemeyer, van Rooij, Lindemann, Willems, & Bekkering, 2010; van Dam, Rueschemeyer, & Bekkering, 2010; Yang, Shu, Bi, Liu, & Wang, 2011). For example, word-evoked motor activation can be left-lateralized if actions are typically performed with one hand ("to write") or more bilateral in case of bi-manual actions ("to clap", Hauk & Pulvermuller, 2011).[14] Furthermore, the subjects' hand preference and motor proficiency modulates language-induced semantic activation in motor systems and adjacent areas (Beilock, Lyons, Mattarella-Micke,

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[14] This differential laterality seems to be independent of handedness and may be driven, in part, by the observation of others' actions (see Hauk & Pulvermuller, 2011).

Nusbaum, & Small, 2008; Hauk & Pulvermuller, 2011; Lyons et al., 2009; Willems, Hagoort, & Casasanto, 2010). These results indicate that semantic properties of linguistic materials along with personal learning history (see Fuster, 1999) are reflected in the sensorimotor system's response.

To what degree do these activations reflecting semantically-related action and perception processes depend on the task applied? Although semantic motor systems activation to words, phrases and sentences has been found in passive speech perception (Pulvermüller, Shtyrov et al., 2005; Shtyrov, Hauk, & Pulvermüller, 2004), passive reading (Hauk & Pulvermüller, 2004; Hauk et al., 2004; Tettamanti et al., 2005), lexical decision (Pulvermüller, Hummel & Härle, 2001; Rueschemeyer, van Rooij, et al., 2010), semantic decision (Kemmerer et al., 2008) and imagery tasks (Tomasino et al., 2007; Willems, Toni, Hagoort, & Casasanto, 2010), it is not omnipresent when action words or sentences are in the input. The repetition of stimulus words within one experiment decreases area-specific activation to word categories (Kiefer, 2005), thus making it less likely to obtain semantic category differences in brain activation (see, e.g., Pulvermüller, Cook, & Hauk, 2012; Tomasino, Fink, Sparing, Dafotakis, & Weiss, 2008; Tomasino et al., 2007). An overt motor task, especially when it involved the right hand or foot, brings about task-related motor activity which may override fine-grained semantic activations (for discussion, see Pulvermüller, Hummel, et al., 2001). For example, Willems et al. used different overt movements with different tasks (eye closing and imagery vs. button press preparation and lexical decision, Willems, Toni, et al., 2010); their task differences (including the absence of activation differences between word categories in hand-motor areas during lexical decisions expressed by finger movements) may therefore be a consequence of preparatory motor processes. Sound/letter detection tasks may also mask semantic motor system activation (Tomasino et al., 2007), as they put an emphasis on phonological processing, which has been shown to be manifest in the motor system too (Section 3.2.1). Note that the processing of phonemes such as /p/ and /t/, even in perception, engages different parts of the motor system (D'Ausilio et al., 2009; Pulvermüller et al., 2006), thus causing phonologically-related somatotopic activation, which may interfere with semantic somatotopy. A study by Poste et al. failed to replicate semantic somatotopy when looking at haemodynamic responses in motor and premotor fields in a ROI[15]-by-ROI manner, although, as significantly larger face-word than leg-word responses were present in the premotor face ROI and the reverse tendency was suggested by the leg-area data (cf. Postle, McMahon, Ashton, Meredith, & de Zubicaray, 2008), it may still be that analyzing data from all ROIs elicited by different action word types could yield reliable interaction effects. Overall, a majority of studies document semantic somatotopy to words and constructions across tasks and languages although some reports failed to do so or showed task or context interferences. A safe way to prevent semantic motor activation is the use of overt motor tasks involving the critical body parts and an emphasis on phonological processing.

The fact that semantic somatotopy persisted in passive tasks and sometimes even under distraction indicates a degree of automaticity of the motor and sensory system activations in semantic processing (Pulvermüller, 2005). What should not, and has not, been claimed, however, is that sensorimotor systems activation is left *unchanged* by task demand or context. Sensorimotor systems activation in semantic processing seems to be automatic insofar as such activation is being elicited even if subjects do not attend to linguistic stimuli. Different tasks, contexts and attention levels may however enhance, reduce or even override sensorimotor systems activations that reflect semantic properties of stimulus utterances. Cancellation of semantic motor systems dynamics is not surprising in the case of massive motor activation when moving a finger or arm, and can be explained in a straightforward manner in the sense of a ceiling effect (Pulvermüller et al., 2001). More interesting types of task- and context-dependent modulations of sensorimotor and semantic activation have been reported by a range of studies (Aravena et al., 2012; Hoenig, Sim, Bochev, Herrnberger, & Kiefer, 2008; Papeo, Corradi-Dell'Acqua, & Rumiati, 2011; Pulvermüller, Cook, et al., 2012; Tomasino, Weiss, & Fink, 2010; Tomasino et al., 2007; van Elk, van Schie, Zwaan, & Bekkering, 2010). These results indicate that, over and above meaning aspects of individual words, the context of tasks and constructions in which stimulus words are embedded contributes to motor system activation. However, it is not sufficient to state that sensorimotor semantic activation is "flexible" (Willems & Casasanto, 2011); rather, the *explanation* of specific patterns of modulation of semantic effects is desirable on the background of neurobiological theory. Such explanations may recur to the activation balance between "embodied" semantic and "disembodied" linguistic circuits, for example those underpinning grammatical items, including function words and inflectional affixes (Pulvermüller, Cook, et al., 2012). An explanation of the modulation of sensorimotor circuit activations with attention levels has been offered in the context of an explicit neurocomputational model (Garagnani et al., 2008). Fig. 3 summarizes results of fMRI studies of action word, phrase and sentence processing in different tasks and languages, which show a degree of agreement across labs and studies (Carota, Moseley, & Pulvermüller, 2012).

4.2. Relative speed of general semantic and specific sensorimotor semantic activation

Semantically-related activation of sensory and motor brain systems has frequently been revealed by haemodynamic neuroimaging, especially fMRI. The majority of these studies suggests an involvement of brain areas important for action and perception in the processing of words and sentences with action- and object-related meaning. However, because of the rather sluggish nature of the hemodynamic responses, fMRI does not allow one to distinguish between *immediate comprehension* processes and later, second-order, "epiphenomenal" *post-understanding inference* (see Glenberg & Kaschak, 2002). Thus, time is of the essence and the critical test needs to scrutinize, with millisecond precision, the time course of activation spreading, asking whether sensorimotor systems activations occur *at or after* the earliest semantic activations known to date.

Semantic processes were once thought to first kick in around 400 ms after a critical stimulus word comes in, being first reflected in the N400 response of the event-related potential (Kutas & Federmeier, 2000). However, recent investigation revealed early responses indexing meaning processing at the word and sentence level (Chanceaux, Vitu, Bendahman, Thorpe, & Grainger, 2012; Hauk, Davis, Ford, Pulvermüller, & Marslen-Wilson, 2006; Penolazzi, Hauk, & Pulvermüller, 2007; Pulvermüller, Assadollahi & Elbert, 2001; Sereno, Brewer, & O'Donnell, 2003), which precede classic N400 effects (Barber & Kutas, 2007; Pulvermüller, Shtyrov, & Hauk, 2009). Such early physiological signs of semantics emerge between 100 and 250 ms after the critical word (or, in sentences, after the word critical for understanding a larger construction) can first be recognized.[16] Crucially, the first sensorimotor system activations fell in the same early time window, thus arguing against

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[15] ROI – Region of Interest.

[16] Please note the recent discovery of even faster, "ultra-rapid" processes related to cohort-activation or lexical access (MacGregor, Pulvermüller, van Casteren, & Shtyrov, 2012), which raises the possibility that even earlier semantic processes may exist.

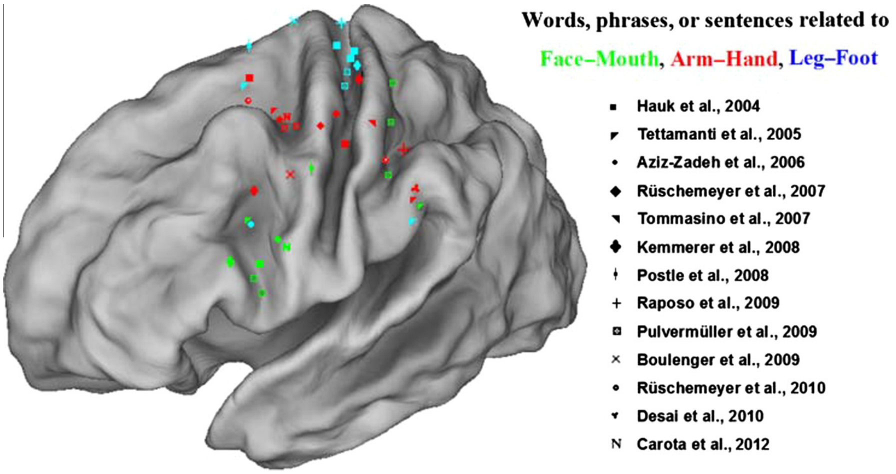

Fig. 3. Review of brain activation loci (most highly significant voxels) in frontoparietal cortex differentially activated by face-, arm-, and leg-related words, phrases and sentences across studies and tasks. Note the somatotopic pattern of activation in pre- (but not post-) central cortex with inferior face-semantic (in green), lateral arm-semantic (red) and dorsal leg-semantic activations (blue, for detailed discussion, see Carota et al., 2012).

a general difference in access latencies of general lexical/semantic and sensorimotor system activations specific to semantic categories. Semantic activations to action words emerged in the motor system (Hauk & Pulvermüller, 2004; Pulvermüller, Härle, & Hummel, 2000; Pulvermüller et al., 2001, 2005; Shtyrov et al., 2004)[17] and to visually-related word categories in the visual system (Moscoso Del Prado Martin, Hauk, & Pulvermüller, 2006). In parallel, behavioral studies also indicated an early semantically-driven emergence of motor system involvement (Boulenger et al., 2006). It therefore appears that fast activations of action–perception systems are quick enough to reflect true comprehension.

A direct comparison of general and category-specific semantic activations in the human brain is possible using paradigms where both play a role. It has been discovered that abstract idiomatic sentences activate certain prefrontal and anterior-temporal areas more strongly than concrete ones (Boulenger et al., 2009; Lauro, Tettamanti, Cappa, & Papagno, 2008). Such multimodal cortex activation may be an index of "disembodied" semantic understanding of aspects of the abstract idioms' meanings. In addition, aspects of the "embodied" meaning of action words included in both idioms and literal sentences (for example "grasp" in "she grasped the idea/apple" or "kick" in "she kicked the habit/ball") was manifest in motor system activation (Boulenger et al., 2009). As such motor system activation reflecting the meaning of constituent action words was present at the point in time when idiomatic and literal sentence meaning were disambiguated, the data seem to suggest a degree of semantic compositional processing at the point in time when sentence meaning was accessed. This addresses a longstanding discussion in semantic theory about whether compositional semantic processes play a role in idiom comprehension or the construction is semantically accessed as a whole without decomposition into its parts (Goldberg, 2006; Lakoff, 1987). Now, crucially, precise mapping-in-time using magnetoencephalography (MEG) showed that the brain correlates of idiomaticy and those of constituent word meaning occurred at the same time, at 150–200 ms after onset of the critical, sentence disambiguating words (not the action words, but rather the critical words "idea" and "apple" in the above examples; see Fig. 4). These results further confirm early semantic activations with the same latency in sensorimotor cortices and in cortical systems that are not specific to sensorimotor modalities. They argue against the possibility that sensorimotor semantic activation might be an epiphenomenon, just following upon, or overspilling from, semantic system activation elsewhere (see Mahon & Caramazza, 2008). If prefrontal and anterior-temporal activations are interpreted as indexes of "disembodied" symbolic system activation, they are manifest together with semantic activation of the action system. At the semantic level, the results suggest that compositional semantic processing of action-related words (precentral cortex) and whole-construction semantic processes (prefrontal and anterior-temporal areas) simultaneously and jointly contribute to idiom comprehension.

4.3. Causal role of sensorimotor systems in semantic processing

Could activity in modality-specific motor and sensory systems have *causal effects* on semantic processing, for example specifically on the processing of words with one type of meaning? For words related to different body parts, this question has been addressed by direct magnetic stimulation to motor cortex. One may predict a cross-over double dissociation of magnetic stimulation to finger- and foot-loci on the recognition of words typically used to speak about arm or leg actions. Since such differential influence of primary motor cortex activation on action word processing has been documented, it is clear that the processes of lexical and semantic access can be influenced by activity in the motor system (Pulvermüller, Hauk, et al., 2005). Further data confirmed a causal effect of motor systems stimulation or engagement on language processing and on the processing of specific semantic word types (Boulenger et al., 2006; Dalla Volta, Gianelli, Campione, & Gentilucci, 2009; Liuzzi et al., 2010; Shebani & Pulvermüller, 2013; Willems, Labruna, D'Esposito, Ivry, & Casasanto, 2011). Similar causal effects exist between systems for visual perception and processing of verbs related to motion (Meteyard, Bahrami, & Vigliocco, 2007; Meteyard, Zokaei, Bahrami, & Vigliocco, 2008).

4.4. Necessity of sensorimotor systems for semantic processing

Whether or not lesions to the motor system indeed cause a *deficit*, that is, a clear impairment, in processing action-language, and motor systems can therefore be considered necessary for processing action–semantic word classes, is a matter of debate (see Arevalo, Baldo, & Dronkers, 2012; Kalenine, Buxbaum, & Coslett, 2010). Hardly denied can be the clear evidence that patient

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[17] However, some work did not confirm early motor system activation to action word processing, but found such activation later (e.g., Papeo, Vallesi, Isaja, & Rumiati, 2009).

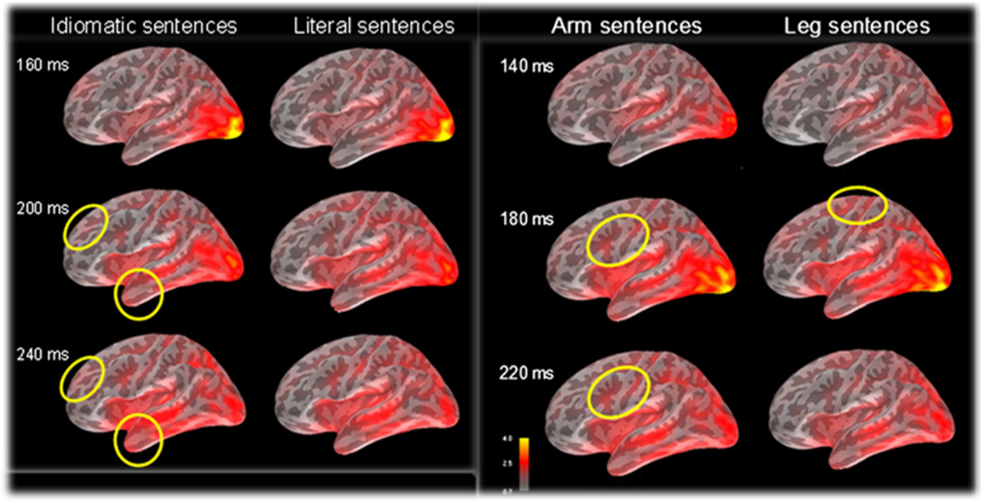

Fig. 4. Time course of brain activation elicited by the sentence-disambiguating word in literal vs. idiomatic sentences (columns on the left) and in sentences (both idiomatic and literal) including hand- vs. leg-related action words (e.g., she grasped/kicked the *idea*, columns on the right). Activation differences between idiomatic and literal sentences were present in dorsolateral-prefrontal and temporopolar areas (yellow circles on the left) already 150–250 ms after the onset of the critical word (e.g., she grasped the *idea;* he kicked the *habit*). At the same time, the action-related meaning of action words included in the sentences was manifest in motor system activation (yellow circles on the right). These results indicate simultaneous processing of the stored meaning of constructions and of that of (some of) the words these constructions are composed of. The data refute the suggestion that motor systems activation results from overspill in other semantic areas (adopted from Boulenger, Shtyrov, & Pulvermüller, 2012).

groups with massive lesions in their motor systems also show a motor cognition deficit and, specifically, a deficit in action verb processing. This has been documented in victims of stroke, Motor Neuron Disease, Parkinson's Disease, and other types of dementia (Bak & Chandran, 2012; Bak, O'Donovan, Xuereb, Boniface, & Hodges, 2001; Bak et al., 2006; Boulenger et al., 2008; Cotelli et al., 2007; Kemmerer, Rudrauf, Manzel, & Tranel, 2012; Neininger & Pulvermüller, 2003).[18] As dissociations were documented between action verbs and nouns with object reference, it may be that the lexical category difference (noun/verb) played a role. However, concordant deficits were reported in conceptual tasks in which the use of language stimuli was avoided (Bak et al., 2006; Kemmerer et al., 2012); therefore, lexical factors cannot explain the full pattern of dissociations between action and object concepts and related words.

At a finer experimental scale, a double dissociation pattern of impairment between arm and leg word memory has recently been documented while healthy subjects continuously performed complex motor tasks. Performing the motor task with the hands led to increased errors in memorizing lists of arm-words, whereas performing it using the legs yielded higher error scores on leg-word working memory tasks (Fig. 5, Shebani & Pulvermüller, 2013). As the primary loci differentially activated by complex arm and leg movement performance are in the motor system, this double dissociation indicates shared processing resources in motor systems between motor movements and semantically congruent action word subcategories.

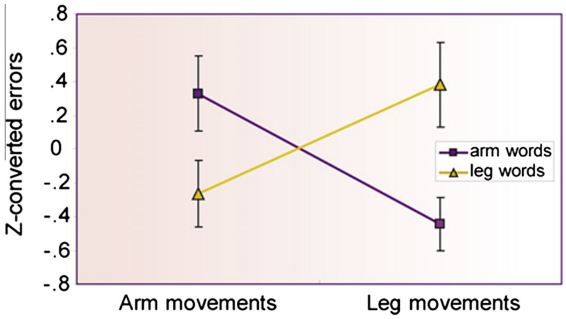

Fig. 5. Moving the hands and legs according to a complex motor scheme impairs working memory for arm- and leg-related words, respectively (adopted from Shebani & Pulvermüller, 2013). These results (given as errors transformed into z-scores) indicate that resources in cortical motor systems engaged by complex body-part-specific movements are necessary for processing of semantically congruent action words.

4.5. Summary

In conclusion, recent work on language materials used to speak about actions and objects makes it difficult to maintain a disembodied semantic perspective separating semantic from sensorimotor processes. Not only would sensory and motor systems become active in the processing of language, this activation also reflects aspects of the meaning of utterances and is even effortless, fast, and the activated modality systems exert an influence, sometimes performance-degrading influence, on category-specific semantic and conceptual processes. These results falsify modular theories of meaning, but are also difficult to reconcile with current minimally-embodied approaches such as the ones put forward by Caramazza and his colleagues (Section 2). Especially, statements about a "non-constitutive" "coloring" and "dressing" role in conceptual/semantic processing of action and perception systems (cf. Mahon & Caramazza, 2008) seem insufficient to provide the required accounts of fast activation spreading to, causal effects of activity in, and deficits after lesions of modality-specific systems.

Therefore, it seems justified to reject the disembodied and minimally-embodied perspectives on semantic processing and to conclude that semantic systems of the mind and brain include action–perception mechanisms as functionally important components. APT, as outlined in Section 3, is consistent with and a-priori predicted many of the novel results summarized here, and, crucially, mechanistically explains not only aspects of semantic "embodiment" but also "disembodiment", e.g. movement of semantic pro-

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[18] Recently, slowing of action verb processing was reported in an imagery (but not in a frequency rating) task in patients with lesions in pre- and post-central sulcus (Tomasino, Ceschia, Fabbro, & Skrap, 2012).

cesses away from sensorimotor systems, as illustrated in the contexts of memory, abstraction, combination and generalization. Future work is needed to spell out the underlying neurobiological mechanisms in more detail, for example taking advantage of further neurocomputational work, and possibly using abstract words and constructions as key examples. In this endeavor, mechanistic neurobiological explanation and detailed accounts of semantic circuits appear most fruitful.

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