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Deeper insights into semantic relations: An fMRI study of part-whole and functional associations

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A B S T R A C T

Cognitive neuroscience research on semantics recognizes a distinction between categorical and associated relations. However, associations can be divided further, such as into part-whole and functional relations. We investigated the neural basis of both relations using a picture–word interference task in an fMRI study. While the left supramarginal gyrus and the right inferior temporal sulcus were activated by part-whole over functional relations, the same applies to the right parahippocampal complex contrasting the functional over part-whole relations. The small effect sizes of our analyses have to be interpreted with caution. While the parahippocampal complex might reflect global scene processing across objects, the inferior temporal sulcus might be involved in the perceptual encoding of object related knowledge and the supramarginal gyrus might represent a convergence zone which implements within object related perceptual features. The current study gives a first indication that the neural bases for part-whole and functional relations seem to be distinguishable.

1. Introduction

The nature of semantics involves understanding objects and their relationships, since objects are rarely known in isolation. Objects can be related by their category memberships (e.g., *car and bus are both vehicles*) or by their associations (e.g., *car and garage are typically seen together*) (Anderson, 1976; Collins & Loftus, 1975; Collins & Quillian, 1970; Estes, Golonka, & Jones, 2011; Lin & Murphy, 2001; also see Caramazza & Mahon, 2003; Chang, 1986; Patterson, Nestor, & Rogers, 2007; Thompson-Schill, 2003). Several semantic priming and naming studies implicate distinct brain networks for these kinds of relations (e.g., Abel et al., 2009; De Zubicaray, Hansen, & McMahon, 2013; Sachs, Weis, Krings, Huber, & Kircher, 2008; Sass, Krach, Sachs, & Kircher, 2009a; Schmidt et al., 2012). While categorically related concepts (e.g., *car* and *bus*) often share intrinsic perceptual features, associative concepts often organize by extrinsic relations, i.e. entities connected within scenes or events (e.g., *car* and *garage*; Estes et al., 2011; Lin & Murphy, 2001). Associations constitute an important aspect of semantic knowledge (Estes et al., 2011), i.e. knowing that *coffee* is categorically related to *tea* is not relevant when somebody gives you a teabag. Instead, you might expect hot water to prepare a cup of tea.

McRae, Khalkhali, and Hare (2012) pointed out that focusing exclusively on associative and categorical relations endorses a “narrow point of view when studying semantic relatedness” (p. 4). To understand the organization of semantic knowledge and related concepts, McRae et al. (2012) advocate the analysis of more fine-grained relationships and propose a taxonomy for different types of semantic relationships (e.g., *similar concepts*, *situation*, or *event*).

In the spirit of these suggestions, we used part-whole and functional relations as subtypes of associative relationships in the present study. As we assigned part-whole and functional relations to associations we dissociate both relations explicitly from a categorical relationship. Part-whole and functional do not fulfill the criteria for categorical relations but belong absolutely to

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semantic relations in general (using the term associations involves implicitly the assignment to semantic relations). We want to emphasize that part-whole and functional relations are no categories. Therefore, we use them as subtypes of associative relations instead of using the term 'semantic relation' as this would also include categories. Again, we want to focus on the differentiation between associative relations and categorical relations but do not want to differentiate between associative and semantic relations. Defining part-whole, those relations encompass notions such as "made-of" (e.g., *coin-copper*) or "component" (e.g., *bike-handlebars*). This relationship is often expressed by "is a part of" (Winston, Chaffin, & Herrmann, 1987), or "has a" (Costa, Alario, & Caramazza, 2005). Importantly, the whole is typically regarded as one object or entity. In contrast, functional relationships include locative relations (e.g., *carpet-ground*) and situationally associated relations (e.g., *flute-note*).[1] Importantly, the terms refer to two distinct but related objects or entities. These different relationships (*intrinsic* versus *extrinsic*) are important in distinguishing between types of associations. "Intrinsic properties refer to the object itself [...] extrinsic properties refer to the object in relation to an external referent" (p. 227, Chatterjee, 2008).

To investigate the conceptual organization within these subtypes of associated semantic relations, we used a picture-naming task. Naming a picture requires several cognitive processing stages from visual processing and object recognition to conceptual preparation, lemma retrieval and selection, morpho-phonological code retrieval, phonological encoding, syllabification, phonetic encoding and articulation of the word (cf., Caramazza, 1997; Chiliant, Costa, & Caramazza, 2003; Dell, 1986; Dell & O'Seaghdha, 1992; Indefrey, 2011; Indefrey & Levelt, 2004; Levelt, 2001; Roelofs, 1992). We capitalized on one method to investigate these stages of picture naming, the picture word interference (PWI) paradigm. In this paradigm, subjects name a picture as fast and accurately as possible while ignoring a distractor word. When the distractor is an associated word, subjects are faster at naming the target picture than when the distractor is not related to the target (e.g., Abdel Rahman & Melinger, 2007; Costa et al., 2005; Sass et al., 2010).

In a recent review, Abdel Rahman and Melinger (2009) proposed a "Swinging Lexical Network" hypothesis (SLNH) to explain facilitation effects for associations in naming. In general, the intention to name a picture (e.g., *car*) induces a spread of activation between related semantic representations at the conceptual level that can be categorical as well as associative (e.g., *bus, motor,* and *crossroad* to *car*). In the case of associatively related distractors, the distractor belongs to a different semantic category and activates different concepts and lexical entries that are categorically and associatively related to the distractor. That means, most of the activated concepts are related to the distractor but not to the target. The activation at the conceptual level from both the picture and the word converges onto the corresponding lexical output of the activated concepts (lexical level). Facilitation depends on the co-activation of related concepts. In the case of associative relations there is no overlap between co-activated target and distractor related lexical entries. In other words, the co-activation of related concepts induces conceptual priming (at conceptual level) but is not strong enough to induce lexical competition (at lexical level) that could produce behavioral interference (conceptual facilitation outweighs lexical interference; Abdel Rahman & Melinger, 2009). Following this account, we expected a facilitation effect for our related condition with associative relations between target picture and distractor word compared to unrelated distractor words.

Another model of speech production, the response exclusion hypothesis (REH; Mahon, Costa, Peterson, Kimberly, & Caramazza, 2007), suggests that facilitation is a lexical effect and occurs because priming at a conceptual level speeds up retrieval times at lexical selection level. This effect "reflects the speed with which production-ready representations can be excluded as potential responses to the target picture" (p. 523, Mahon et al., 2007) from the articulatory buffer. Response times (RTs) reflect how fast the distractor can be excluded, i.e., both associative and unrelated distractor words are equally irrelevant and can be eliminated easily from the output buffer. Facilitation is observed as the related distractor primes the target more than the unrelated distractor and increases the person's speed of naming the picture (Dhooge & Hartsuiker, 2010).

For our purposes, the relevance of both models is that a behavioral pattern of facilitation implies that the effect of the associated distractor on naming pictures is occurring at either lexical level (SLN) or at post-lexical level (REH). Costa et al. (2005) reported facilitation for part-whole objects and explained this finding as support for the REH. The part-whole distractor is equally irrelevant than the unrelated distractor but it speeds up the selection by priming the picture name. Interestingly, Roelofs, Piai, and Schriefers (2013) provided support for the lexical competition account as an alternative explanation for Costa et al. (2005) findings: the relationship of the pictures can be described as having strong associative relations that typically induce facilitation. The facilitation effect for associations can also be explained by the SLN.

Recent reviews of functional magnetic resonance imaging studies (fMRI; e.g., Bookheimer, 2002; Indefrey, 2011; Indefrey & Levelt, 2004; Price, 2010) attempt to clarify the relation between neuroanatomic structures and their functional role in speech production. Indefrey (2011) suggested that "core components of word production" (p. 8, Indefrey, 2011) are the left inferior frontal gyrus, the left precentral gyrus, the supplementary motor area, the left superior and middle temporal gyrus, the right superior temporal gyrus, the left fusiform gyrus, the left anterior insula, the left thalamus, and the cerebellum. Our picture naming task is one way to study the neural correlates of speech production. The selected stimuli material consisted of non-living objects only. Naming object pictures requires object knowledge, sensory-motor processes, such as the object's visual properties and functional use (Chatterjee, 2008). The conceptual analysis of objects and its neural basis is debated. Martin (2007) summarized in his review activations in the left fusiform gyrus, the left posterior middle temporal gyrus, the left ventral premotor cortex and the left intraparietal sulcus that represented visual form and action properties for common tools. Kalénine et al. (2009) found distinct neural activations within the left inferior parietal cortex (particularly the supramarginal gyrus) in relation to the kind of manipulation of associatively related objects (i.e. manipulable versus non-manipulable objects). Until now, only a few fMRI studies have examined the impact of semantic associations on picture naming (Abel, Dressel, Weiller, & Huber, 2012; Abel et al., 2009; De Zubicaray et al., 2013; Mechelli, Josephs, Lambon Ralph, McClelland, & Price, 2007). The used stimuli consisted of different categories of objects, e.g. living and non-living items. The results revealed that several regions are activated during word production (bilateral angular gyrus, left fusiform gyrus and left middle temporal gyrus), mental imagery (bilateral middle and superior occipital gyrus) and episodic memory (left precuneus). The focus on fine-grained associative concepts might involve additional activation within the inferior parietal lobe, parahippocampal gyri, dorso- and ventromedial prefrontal cortex and posterior cingulate gyrus that all were summarized to be involved in conceptual processing (Binder et al., 2009).

The question of how fine-grained differences within associated relations produce different behavioral and neural responses remains open. Can we make meaningful distinctions within a heterogeneous knowledge system such as the set of associated relations?

[1] The stimuli used in the present study are one possible fine-grained classification.