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Research report

Differential cortical contribution of syntax and semantics: An fMRI study on two-word phrasal processing

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ABSTRACT

Linguistic expressions consist of sequences of words combined together to form phrases and sentences. The neurocognitive process handling word combination is drawing increasing attention among the neuroscientific community, given that the underlying syntactic and semantic mechanisms of such basic combinations—although essential to the generation of more complex structures—still need to be consistently determined. The current experiment was conducted to disentangle the neural networks supporting syntactic and semantic processing at the level of two-word combinations. We manipulated the combinatorial load by using words of different grammatical classes within the phrase, such that determiner-noun combinations (this ship) were used to boost neural activity in syntax-related areas, while adjective-noun combinations (blue ship) were conversely used to measure neural response in semantic-related combinations. By means of functional magnetic resonance imaging (fMRI), we found that syntax-related processing mainly activates the most ventral part of the inferior frontal gyrus (IFG), along the frontal operculum (FOP) and anterior insula (aINS). Fine-grained analysis in BA44 confirmed that the most inferior-ventral portion is highly sensitive to syntactic computations driven by function words. Semantic-related processing on the contrary, rather engages the anterior dorsal part of the left IFG and the left angular gyrus (AG) that is two regions which appear to perform different functions within the semantic network. Our findings suggest that syntactic and semantic contribution to phrasal formation can be already differentiated at a very basic level, with each of these two processes comprising non-overlapping areas on the cerebral cortex. Specifically, they confirm the role of the ventral IFG for the construction of syntactically legal linguistic constructions, and the prominence of the more anterior IFG and the AG for conceptual semantics.

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1. Introduction

Human language is characteristically defined as a highly productive cognitive ability: words can be continuously combined together to create an infinite number of new expressions of increasing complexity. To comprehend such novel expressions in an effective way, our brain needs to do two things: it has to assess what the meaning of the individual words mean when put together, and it has to retrieve the abstract underlying structure binding such expressions. These two processes refer to the linguistic aspects of semantics and syntax. Specifically, semantic composition drives the combination of the meanings of the individual words to form meaningful expressions. These combinational computations are the most fundamental mechanisms at the root of every language (Hauser, Chomsky, & Fitch, 2002).

Syntactic computations, conversely, implement the rules that govern the abstract architecture of the same expressions (Chomsky, 1995). Traditionally, neurolinguistic investigations have tried to manipulate semantic composition and syntactic computations within the context of full sentences for a review see Friederici (2011). Semantic composition has been mostly examined either by varying the semantic load in sentences with or without pseudowords to reduce semantics information (Humphries, Binder, Medler, & Liebenthal, 2006; Mazoyer et al., 1993; Pallier, Devauchelle, & Dehaene, 2011), by varying semantic complexity to contrast short sentences against longer sentences or narratives (Pallier et al., 2011; Stowe et al., 1998; Xu, Kemeny, Park, Frattali, & Braun, 2005), or by evaluating semantic plausibility in a specific context (Newman, Ikuta, & Burns, 2010; Zhu et al., 2009, 2013). Syntactic computations, conversely, have been mainly investigated by comparing sentences to word lists lacking syntactic information (Friederici, Meyer, & Von Cramon, 2000; Humphries et al., 2006; Mazoyer et al., 1993; Pallier et al., 2011; Stowe et al., 1998; Xu et al., 2005), by evaluating different degrees of syntactic complexity (Bornkessel, Zysset, Friederici, von Cramon, & Schlesewsky, 2005; Makuuchi, Bahlmann, Anwander, & Friederici, 2009), by focusing on syntactic errors (Friederici, Ruschemeyer, Hahne, & Fiebach, 2003; Vandenberghe, Nobre, & Price, 2002), or by using syntactic priming (Segaert, Menenti, Weber, Petersson, & Hagoort, 2012). The sentential level however might not be the best approach to explore the neural basis of basic compositional processes in the semantic and syntactic domain since multiple combinations of words and complex structures tend to involve additional mechanisms external to syntactic computations and semantic composition. These additional mechanisms are working memory and storage (Makuuchi & Friederici, 2013; Makuuchi et al., 2009; Meyer, Obleser, Anwander, & Friederici, 2012; Santi & Grodzinsky, 2007), cognitive control and ambiguity resolution (Badre, 2008; Koechlin, Ody, & Kouneiher, 2003), and at the text level even integration into the context of discourse (Egidi & Caramazza, 2013).

More recently, researchers have started to look at compositional processing in the semantic and syntactic domain at more basic levels, investigating how the brain behaves during the combination of very simple two- or three-word phrasal structures, such as "blue boat", "this boat" or "on the boat". Within the neurolinguistic tradition, the expression *basic levels* of linguistic processing therefore refers to the build-up of simple structures beyond single words, where the combination of independent lexical elements (e.g. an adjective and a noun, or a determiner and a noun) are combined together to form elementary phrases or sentences at the root of linguistic complexity. Evidence from different languages is now available, including English (Bemis & Pylkkanen, 2011, 2012a,b, 2013; Del Prato & Pylkkanen, 2014; Westerlund & Pylkkanen, 2014; Westerlund, Kastner, Al Kaabi, & Pylkkanen, 2015; Zhang & Pylkkanen, 2015), Spanish (Molinaro, Carreiras, & Duñabeitia, 2012; Molinaro, Paz-Alonso, Dunabeitia, & Carreiras, 2015), and German (Zaccarella & Friederici, 2015a; Zaccarella, Meyer, Makuuchi, & Friederici, 2015).

Focusing on the semantic domain, the first of these studies (Bemis & Pylkkanen, 2011) used adjective-noun combinations and reported increased cortical activity for phrasal composition in the anterior temporal lobe, ATL (and in the ventral prefrontal cortex). In this study, participants were asked to combine together in a visual task a descriptive adjective "red" with a noun "boat" to be matched with a picture. The ATL was found equally active when the same types of stimuli were processed in the auditory modality (Bemis & Pylkkanen, 2012a). Given the type of stimulus used, the authors concluded that the ATL might be the region particularly engaged during semantic composition, deriving the meaning of a simple phrase like 'red boat' from the conjunction of the two simpler concepts of "redness" and "floating object", expressed by the adjective 'red' and the noun 'boat' respectively (Smith, 1984). The authors base their interpretation on findings from single word processing, for which activity in the ATL was reported when words had to be classified conceptually as referring to a living or non-living object (Price, Moore, Humphreys, & Wise, 1997). At the clinical level, evidence supporting a semantic role for the ATL, comes from patient studies which traditionally link the region to semantic processing deficits (e.g. semantic dementia) following temporal lobe atrophy (Bonner et al., 2009; Galton et al., 2001; Gorno-Tempini et al., 2004; Rohrer et al., 2009). Patients with semantic dementia generally show deficit in conceptual knowledge for various domains (Gorno-Tempini et al., 2011; Hodges et al., 2010; Snowden, 1995). As such, the ATL might integrate information associated with the respective concepts during the processing of words (Lambon Ralph, Sage, Jones, & Mayberry, 2010; Patterson, Nestor, & Rogers, 2007; Visser, Jefferies, & Lambon Ralph, 2010). According to this view specific conceptual information (e.g. the boat's shape, color, sound, world-knowledge, etc.) is stored in corresponding cortical areas, while the ATL serves as an amodal hub to fuse the different aspects of conceptual information.

A second region proposed to be relevant for semantic composition is the angular gyrus (AG) (Binder, Desai, Graves, & Conant, 2009). The AG was found to be involved in addition to the ATL during the construction of two-word semantic composition, regardless of modality, although the AG activated at a later time point than the anterior temporal region (Bemis & Pylkkanen, 2012a). Furthermore, it was shown that activation in AG varied as a function of plausibility by comparing meaningful (e.g. plaid jacket) with non-meaningful