NeuroImage 124 (2016) 194–203

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/ynimg

# Composition of complex numbers: Delineating the computational role of the left anterior temporal lobe

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ARTICLE INFO

*Article history:*
Received 2 June 2015
Accepted 22 August 2015
Available online 30 August 2015

*Keywords:*
Conceptual combination
Magnetoencephalography
Left anterior temporal lobe
Numerical quantification
Complex number composition

ABSTRACT

What is the neurobiological basis of our ability to create complex messages with language? Results from multiple methodologies have converged on a set of brain regions as relevant for this general process, but the computational details of these areas remain to be characterized. The left anterior temporal lobe (LATL) has been a consistent node within this network, with results suggesting that although it rather systematically shows increased activation for semantically complex structured stimuli, this effect does not extend to number phrases such as 'three books.' In the present work we used magnetoencephalography to investigate whether numbers in general are an invalid input to the combinatory operations housed in the LATL or whether the lack of LATL engagement for stimuli such as 'three books' is due to the quantificational nature of such phrases. As a relevant test case, we employed complex number terms such as 'twenty-three', where one number term is not a quantifier of the other but rather, the two terms form a type of complex concept. In a number naming paradigm, participants viewed rows of numbers and depending on task instruction, named them as complex number terms ('twenty-three'), numerical quantifications ('two threes'), adjectival modifications ('blue threes') or non-combinatory lists (e.g., 'two, three'). While quantificational phrases failed to engage the LATL as compared to non-combinatory controls, both complex number terms and adjectival modifications elicited a reliable activity increase in the LATL. Our results show that while the LATL does not participate in the enumeration of tokens within a set, exemplified by the quantificational phrases, it does support conceptual combination, including the composition of complex number concepts.



## Introduction

Understanding the brain basis of linguistic creativity is a fundamental goal for the cognitive neuroscience of language: what is the neurobiology of our ability to create an infinity of conceptual representations from the basic building blocks of language? Large networks of brain areas have been proposed to partake in the brain's "semantic network" (Binder et al., 2009; Binder and Desai, 2011) including the left inferior frontal cortex (e.g., Hagoort and Indefrey, 2014), the superior temporal gyrus (e.g., Friederici, 2011), the angular gyrus (e.g., Price et al., 2015) and the left anterior temporal lobe (LATL). Each of these regions has been proposed to carry a role in the combinatory processing of language. Damage to the angular gyrus can result in a wide variety of neuropsychological conditions affecting language, visuo-spatial processing and number cognition and thus it has been proposed as a high-level supramodal integration area, with the combination of concepts as part of its computational profile (Binder et al., 2009). The anatomical connectivity of the angular gyrus further conforms to a high level integrative role as it receives its input mostly from other association areas as opposed to primary sensory cortices (Bonner et al., 2013; Mesulam, 2000; Pandya and Seltzer, 1982; Yeterian and Pandya, 1985). The left inferior frontal cortex has also been associated with a multitude of functions, including phonological (Heim et al., 2008), semantic (Thompson-Schill et al., 1997) and syntactic processing (Stromswold et al., 1996), but within combinatory processing, its contribution has most commonly been proposed to be syntactic (Indefrey, 2012; Indefrey et al., 2001b; Hagoort and Indefrey, 2014; Friederici, 2011; Pallier et al., 2011; Tyler et al., 2011). Similar sensitivity to syntactic stimulus properties has been observed in posterior superior temporal cortex (Hagoort and Indefrey, 2014; Pallier et al., 2011).

However, as regards the semantic aspects of combinatory processing, multiple methodologies, including neuroimaging, electrophysiology and patient research, have produced an internally highly consistent body of work strongly implicating the LATL as a basic site for semantic combination. Core evidence for this include hemodynamic and neuropsychological research proposing that this brain area acts as a 'semantic

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http://dx.doi.org/10.1016/j.neuroimage.2015.08.049
1053-8119/

hub' in which conceptual representations are bound together and processed by a common set of neurons (Bright et al., 2004; Clarke et al., 2011, 2013; Gauthier et al., 1997; Grabowski et al., 2001; Rogers et al., 2006; Tyler et al., 2004) as well as sentence processing studies showing that structured sentences elicit greater LATL activity than meaningless sentences or word lists (Friederici et al., 2000; Humphries et al., 2006, 2007; Mazoyer et al., 1993; Pallier et al., 2011; Rogalsky and Hickok, 2009; Stowe et al., 1998; Vandenberghe et al., 2002; Xu et al., 2005). More recently, magnetoencephalography (MEG) studies on minimal combinations of two words have demonstrated that this activity relates to very basic combinatory operations as opposed to sentence-level phenomena both in comprehension (Bemis, and Pylkkänen, 2011, 2012) and in production (Del Prato and Pylkkänen, 2014; Pylkkänen et al., 2014).

While this large dataset on the LATL is still compatible with many definitions of “semantic processing”, the robustness of these findings and their generality across multiple methodologies presents an opportunity for a systematic investigation of the computational details of this activity. One step towards sharpening our understanding involves recent MEG results on language production (Del Prato and Pylkkänen, 2014), where the modification of object denoting nouns with color adjectives (*blue cups*) engaged the LATL, while numerical quantification of the same nouns (*two cups*) did not. Given that both of these combinations involve semantic composition, these data are incompatible with a general semantic composition account of the LATL. Instead, they suggest a narrower computation, perhaps better characterized as a type of “conceptual combination”, a label employed in the concepts and categories literature for a host of cases where, intuitively, the combination of two concepts serves to form a more complex one, typical examples being adjective–noun and noun–noun combinations. Given that in phrases such as *two cups*, *two* does not add a feature to the concept denoted by *cup* but rather enumerates the number of tokens in a set of cups, such cases would, by hypothesis, fall outside the definition of conceptual combination that is relevant for the LATL. Related evidence for the conceptual nature of the LATL include the sensitivity of its combinatory response to conceptual specificity (Westerlund and Pylkkänen, 2014; Zhang and Pylkkänen, 2015) and the correlation between the LATL activation elicited by specific concepts like *boy* and the product of the activations for their constituent concepts (i.e., *male* and *child*) (Baron and Osherson, 2011).

The purpose of the current experiment was to further characterize which input elements and specific computations constitute the “conceptual combinations” which drive activity within the LATL. Specifically, our study was designed around the question of whether complex number terms, such as *thirty-two*, would elicit combinatory activity in the LATL, despite its insensitivity to numerical quantification. Since this study builds on the results of Del Prato and Pylkkänen (2014), which was conducted in production, the current study is also a production study. Several prior studies have addressed the neurobiological similarity of combinatory operations in production vs. comprehension, with results compellingly showing that similar regions are recruited for composition whether the participant is comprehending or producing language (Hagoort and Indefrey, 2014; Menenti et al., 2011, Segaert et al., 2012; Pylkkänen et al., 2014). On the basis of this, one would predict the results of the current study to be replicable in comprehension. Further, as described in Methods, our production paradigm allowed us to keep the physical stimulus almost completely constant across conditions (cf., Del Prato and Pylkkänen, 2014; Pylkkänen et al., 2014), which was particularly useful given that confounding low level factors are often an issue in language studies. The combination of our two-word paradigm together with the millisecond time-resolution of MEG circumvents the principle obstacle behind electrophysiological investigations of sentence production, i.e., that meaningful electrophysiological data is extremely difficult to collect while the mouth is moving. However, the syntactic and semantic planning of small two-word phrases is thought to occur entirely prior to the onset of articulation (Alario et al., 2002; Meyer, 1996; Schriefers et al., 1999) and thus with a technique capable of capturing these planning stages millisecond-by-millisecond, we are able to measure combinatory processing (Pylkkänen et al., 2014). An added advantage of the detailed time resolution is that it allows us to separate different effects within the same region at different times.

Behavioral research on conceptual combination has classically been quite focused on one particular domain; the modification of nouns (e.g., Medin and Shoben, 1988; Murphy, 1990; Wisniewski, 1996; Hampton, 1997). Given that the LATL is at least activated by the core cases of conceptual combination, as evidenced by the many studies on adjective–noun combinations (comprehension: Bemis, and Pylkkänen, 2013; Westerlund and Pylkkänen, 2014 and production: Del Prato and Pylkkänen, 2014; Pylkkänen et al., 2014), it now becomes possible to concretely test what types of semantic combinations drive this activity. In other words, what is the brain's definition of “conceptual combination”?

Number words are a particularly interesting test case for this purpose as they are a very multifaceted word class in terms of the position and semantic functions they can fulfill in a sentence (Hurford, 1975). The most widely spread view states that (simplex) cardinals such as ‘one’, ‘two’ and ‘three’ are determiners (Barwise and Cooper, 1981; Bennett, 1975; Montague, 1974; Scha, 1984) and they have traditionally been treated either as generalized quantifiers (Montague, 1974; Barwise and Cooper, 1981) or restrictive modifiers (Link, 2002) when they precede the noun. However, according to Hurford (1975, 1987, 2001, 2003) and Ionin and Matushansky (2006): “when not acting as modifiers, the vast majority of simplex cardinals are singular nouns and belong to one or another open lexical class available in a language”. Therefore, number words do not fall clearly in either open or close class word categories and can interestingly occupy the place of both in a noun phrase. This unique feature provides the opportunity to create different combinations and investigate to which extent the conceptual details of the input elements matter by creating a number of instinctively different combinations, while keeping the input elements constant.

The purpose of this experiment was to develop some understanding of the bounds and generality of the computations performed in the LATL regarding exactly what types of representations it combines. Particularly, as numerical quantification did not elicit conceptual combination in the LATL (Del Prato and Pylkkänen, 2014), our focus was on assessing whether this was because the LATL does not perform quantificational operations — which was Del Prato and Pylkkänen's interpretation — or because numbers in general are not a valid input to the LATL's combinatory mechanism. As a critical test case, we employed complex number terms such as *thirty-two*, which at least intuitively, may be instances of conceptual combination with numbers as the input. If such combinations engage the LATL while numerical quantifications do not, this would be evidence that it is the nature of the combinatory operation as opposed to the nature of the input items that matters for the LATL.

Like Del Prato and Pylkkänen (2014), our study employed a production paradigm where subjects named perceptually parallel displays in different ways, depending on task instruction. In all, our design included three combinatory conditions: complex number terms, numerical quantifications, and adjectival modifications, all of which were compared to non-combinatory list controls (Fig. 1). We aimed for minimal lexical differences in the produced utterances, and thus, given that complex number terms involve number words in both first and second position (*thirty two*), we designed the numerical quantifications to also have this property (e.g., *three twos*) while adjectival modifications involved a combination of a color adjective and a number term (*green twos*). As a primary non-combinatory control, we used lists consisting of two single-digit numbers (*two*, *three*), but also included lists consisting of a decade number and a single-digit number (*thirty*, *two*), given that lexically, this yields a form identical to the complex number term. However, given that decade numbers are themselves potentially complex, this latter control was not obviously non-combinatory, and thus could have been predicted to pattern somewhere between the combinatory conditions and our single-