Cognition 170 (2018) 49–63

Contents lists available at ScienceDirect

Cognition

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

Original Articles

The priming of basic combinatory responses in MEG

Esti Blanco-Elorrieta[a,b], Victor S. Ferreira[c], Paul Del Prato[a], Liina Pylkkänen[a,b,d,*]

[a] Department of Psychology, New York University, New York, NY 10003, USA
[b] NYUAD Institute, New York University Abu Dhabi, Abu Dhabi, P.O. Box 129188, United Arab Emirates
[c] Department of Psychology, University of California, San Diego, La Jolla, CA 92093-0109, USA
[d] Department of Linguistics, New York University, New York, NY 10003, USA

ARTICLE INFO

Keywords:
Priming
Composition
Language production
Magnetoencephalography
Left anterior temporal lobe
Semantics

ABSTRACT

Priming has been a powerful tool for the study of human memory and especially the memory representations relevant for language. However, although it is well established that lexical access can be primed, we do not know exactly what types of computations can be primed above the word level. This work took a neurobiological approach and assessed the ways in which the complex representation of a minimal combinatory phrase, such as *red boat*, can be primed, as evidenced by the spatiotemporal profiles of magnetoencephalography (MEG) signals. Specifically, we built upon recent progress on the neural signatures of phrasal composition and tested whether the brain activities implicated for the basic combination of two words could be primed. In two experiments, MEG was recorded during a picture naming task where the prime trials were designed to replicate previously reported combinatory effects and the target trials to test whether those combinatory effects could be primed. The manipulation of the primes was successful in eliciting larger activity for adjective-noun combinations than single nouns in left anterior temporal and ventromedial prefrontal cortices, replicating prior MEG studies on parallel contrasts. Priming of similarly timed activity was observed during target trials in anterior temporal cortex, but only when the prime and target shared an adjective. No priming in temporal cortex was observed for single word repetition and two control tasks showed that the priming effect was not elicited if the prime pictures were simply viewed but not named. In sum, this work provides evidence that very basic combinatory operations can be primed, with the necessity for some lexical overlap between prime and target suggesting combinatory conceptual, as opposed to syntactic processing. Both our combinatory and priming effects were early, onsetting between 100 and 150 ms after picture onset and thus are likely to reflect the very earliest planning stages of a combinatory message. Thus our findings suggest that at the earliest stages of combinatory planning in production, a combinatory memory representation is formed that affects the planning of a relevantly similar combination on a subsequent trial.

1. Introduction

Language is a combinatory system in which a finite set of basic building blocks serves as the input to a generative engine capable of yielding an infinitude of expressions. Behavioral and brain science has made important advances in our understanding of the cognitive and neurobiological basis of the atomic units of this system – what we represent about them, where they are represented in the brain, and how the cognitive and neural representations of these units relate to other cognitive and neural domains. What is thus far less understood, however, is how neurocognitive mechanisms combine the pieces together into the structures that form more complex linguistic expressions. Here, we present two experiments that use a novel combination of behavioral and neuroscience techniques to gain new insights into the basic processes that combine words into the next level of complex linguistic structure.

In the behavioral literature, *priming* was one of the most foundational discoveries in the psychology of language (Meyer & Schvaneveldt, 1971; Meyer & Schvaneveldt, 1976), having inspired vast bodies of research characterizing the memory representations relevant for linguistic processing (for review, see Neely, 1991). However, whereas theories of how words are represented have been critically shaped by priming research, the extent to which computations above the word level can be primed remains less understood. That is, whereas the arbitrary relation between the sounds and meanings of lexical items makes it necessary to store words in memory, most combinations of words are formed via a generative procedure, and thus a processor that creates no memory representations for complex structures is at least conceivable.

* Corresponding author at: Departments of Linguistics and Psychology, New York University, New York, NY 10003, USA.
E-mail address: liina.pylkkanen@nyu.edu (L. Pylkkänen).

http://dx.doi.org/10.1016/j.cognition.2017.09.010
Received 28 June 2016; Received in revised form 14 September 2017; Accepted 15 September 2017

However, research on sentence processing has shown that at least some aspect of the processing of syntactic structures can be primed (Bock, 1986), especially if the primes and targets share some lexical material (Pickering & Branigan, 1998). The majority of this research has employed language production, showing that the likelihood of a speaker using a certain syntactic structure on a target trial increases if they have been exposed to that structure on a prime trial (for reviews see e.g., Ferreira & Bock, 2006; Pickering & Ferreira, 2008). This effect could reflect processing at many different levels: it could reflect the priming of the particular sequence of combinatory operations required to build the relevant structure, it could reflect a fleeting memory representation of the built structure, or it could reflect the decision processes of the speaker to construct a particular structure as opposed to a competing one. In comprehension, structural priming manifests as reduced processing times for a previously encountered structure. However, compared to production, these effects have been less robust, less straightforward – typically involving ambiguous materials (Branigan, Pickering, & McLean, 2005; Cuetos, Mitchell, & Corely, 1996) – and less independent of lexical overlap (Branigan et al., 2005). Thus it could be that priming in production is, in fact, largely driven by the decision process of choosing a structure, and when this is removed, less priming is observed. This possibility is corroborated by the fact that ambiguity easily brings out priming in comprehension, given that ambiguity resolution also involves a decision process between competing representations. In all, although the structural priming literature clearly shows that priming can be observed above the word level in sentence processing, it does not yet tell us exactly which processing levels can be primed and which cannot.

To approach this question systematically, one would ideally start with the simplest processes that lie closest to lexical access, given that lexical access can be primed. The next step up in the computational hierarchy of language is the basic combinatory operations that build phrases out of words. Could the act of combining *black* with *cat* be primed? If yes, the composition of *black cat* should facilitate the subsequent composition of, say, *brown table*, which is built exactly by the same combinatory rule although none of the same words are involved. In other words, does the application of the abstract adjective + noun rule form a primeable memory representation?

We addressed this basic question by measuring the earliest stages of combinatory processing with magnetoencephalography (MEG), which has already been used to characterize the brain correlates of basic composition across a series of studies (Bemis & Pylkkänen, 2011; Bemis & Pylkkänen, 2013a; Bemis & Pylkkänen, 2013b; Blanco-Elorrieta & Pylkkänen, 2016a; Pylkkänen, Bemis, & Elorrieta, 2014; Westerlund & Pylkkänen, 2014; Westerlund, Kastner, Al Kaabi, & Pylkkänen, 2015; Zhang & Pylkkänen, 2015). The result relevant for the current study is that both the comprehension and production of adjective-noun combinations engages the left anterior temporal lobe (LATL) and the ventromedial prefrontal cortex (vmPFC) as compared to non-combinatory one or two word stimuli (Bemis & Pylkkänen, 2011; Pylkkänen et al., 2014). Replications of these results for full sentences (Brennan & Pylkkänen, 2012) and other types of two-word phrases (Westerlund et al., 2015) suggest that the effects reflect basic and generalizable combinatory processes. While the same regions have been implicated for both production and comprehension (Bemis & Pylkkänen, 2011; Pylkkänen et al., 2014), the timing of the activations, unsurprisingly, differs between the two. In comprehension, effects of composition occur first in the LATL at around 200–250 ms, and then in the vmPFC at ∼350–400 ms (Bemis & Pylkkänen, 2011). However, combinatory effects in the LATL seem to be limited to combinations that are in some sense "simple:" for example, effects of adjectival modification are not seen for head nouns that are conceptually highly specific, suggesting that by 200 ms, the meanings of these nouns have not been sufficiently accessed to allow composition (Pylkkänen, 2015; Westerlund & Pylkkänen, 2014). Further, there is evidence that the modifications need to be intersective in order for the LATL to engage (Poortman & Pylkkänen, 2016; Ziegler & Pylkkänen, 2016). LATL effects of composition have also been reported for compounds, but only for transparent compounds (Brooks & de Garcia, 2015), which is also consistent with prior findings from EEG (MacGregor & Shtyrov, 2013). The vmPFC, on the other hand, does not seem limited to "simple" compositions, in fact, its combinatory role was first characterized for compositions that involve syntax-semantics mismatches (Brennan & Pylkkänen, 2008; Brennan & Pylkkänen, 2010; Pylkkänen, Martin, McElree, & Smart, 2009; Pylkkänen & McElree, 2007). Thus in comprehension, the LATL is likely to reflect an early "conceptual sketch pad," only composing the simplest, most readily accessible meanings, with the vmPFC reflecting a much later stage, perhaps encoding the output of a multi-stage composition process (Pylkkänen, 2015). Such vmPFC encoding of the combinatory meaning could then plausibly serve as the starting point in production, in which a message level meaning initiates a series of computations in order to finally produce an articulatory plan. Indeed, vmPFC effects in production have onset as early at 180 ms after picture onset, consistent with this hypothesis (Pylkkänen et al., 2014). LATL effects in production have occurred either slightly after or in parallel with vmPFC effects (Pylkkänen et al., 2014), suggesting that combinatory activity in the LATL may be relatively time locked to an early time window, whether elicited by production or comprehension. This timeline also fits with the EEG findings of MacGregor and Shtyrov (2013), who found transparent compounds to be processed combinatorially in an early time window (130–160 ms).

Building on this work in our priming paradigm, we first localized combinatory processing during the prime, replicating the prior work (Pylkkänen et al., 2014), and then assessed whether activity in the same spatio-temporal location shows priming for a combinatory target when the prime is also combinatory. Importantly, our study is the first to offer not just a measurement of the priming effect on the target but also a measurement of the corresponding, unprimed, activity during the prime. Given that structural priming has been most robust in production, we used picture naming as our main task. Critically, the fine temporal resolution of MEG allowed the measurement of the syntactic and semantic planning stages between picture onset and articulation (Pylkkänen et al., 2014), given that the planning of two-word phrases is thought to have entirely completed prior to the onset of articulation and its accompanying motion artifacts (Alario, Costa, & Caramazza, 2002; Meyer, 1996; Schriefers, De Ruiter, & Steigerwald, 1999).

Specifically, on prime trials, subjects named colored objects with adjective-noun combinations (*red boat*) and outlines of objects with single nouns (*boat*). The targets always involved adjective-noun productions, with the priming manipulation consisting of whether the prime and target only shared a structure (Structural: *red boat* – *blue bell*), shared a structure and both words (Full Overlap: *red boat* – *red boat*), or only shared the noun (Lexical: *boat* – *red boat*). Priming of composition was assessed against the last condition, in which the prime was non-combinatory, and the fully overlapping condition was included to safeguard the study against a null result, should there be no purely structure driven priming.

To further characterize the computational stages responsible for possible priming, our design also included two tasks where instead of naming the primes, the primes were more shallowly processed. In the lowest level "View" task, subjects only viewed the prime, allowing us to assess whether any obtained effects were due to the visual properties of the stimuli. In the mid-level "Conceptual" task, we forced subjects to attend to the semantic properties of the primes without actually naming them. This task was intended to diagnose whether priming in target productions may be driven by the comprehension of the complex semantics present in the pictures (i.e., the conceptual combination of a color and an object), a process that has previously been shown to elicit combinatory effects in the vmPFC (Bemis & Pylkkänen, 2013). Thus, in all, the study was a 2 × 3 × 3 factorial design crossing Priming (Prime, Target), Prime Task (Naming, Conceptual, View) and Prime Type (FullOverlap, Structural, Lexical), as depicted in Fig. 1A. In addition to the MEG data, speech onset of the target productions was used as a dependent measure.