Précis of *Simple Composition During Language Processing: An MEG Investigation*

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Introduction

A centerpiece in human cognition is the extraordinary ability to produce and comprehend language. Through language, we are able to convey an unlimited number of complex ideas with incredible speed and efficiency. This capacity derives from the compositional nature of human language – its ability to construct complex meanings through the productive combination of simpler pieces. Words (*quietly, blue, danced, at, flamingo, the, dawn*) can be combined into phrases (*danced quietly, at dawn*, *the blue flamingo*), which in turn combine into sentences that express complex ideas (*at dawn the blue flamingo danced quietly*). The power of compositionality is that complicated expressions can be easily produced and understood without any previous exposure to the final meaning; it is enough simply to know the meanings of the individual pieces and how they are structurally combined.

Understandably, this important ability has given rise to several disciplines of study that seek to explain different facets of our linguistic ability. Formal linguistics attempts to carefully characterize the precise representations and rules that underlie linguistic knowledge; psycholinguistics investigates the cognitive mechanisms by which this knowledge is utilized; and neurolinguistics seeks to uncover the neural implementation of these mechanisms. These fields, in turn, each draw heavily on contributions from computer science (such as for analyzing of formal languages), statistics (such as for developing computational parsing models), and physics (such as for extracting information from neuroimaging and electrophysiological measurements). Unfortunately, to date the concrete realization of this theoretical interdisciplinary nature has been slow.

In large part, the failure to more closely align these different disciplines has been due to the complexity of language, which permeates the investigations of all linguistic disciplines. Almost universally, the study of combinatorial mechanisms in language processing, which supply its compositional power, has relied upon complex expressions that push the bounds of our linguistic capabilities. For example, center-embedded[1, 2] and garden-path sentences[3, 4] have long been staples of linguistic study across all disciplines. This complexity of stimuli has led to a complexity of results and, consequently, a lack of clarity in their interpretation, as many diverse mechanisms, both linguistic and otherwise, are required to process such expressions. Ultimately, more energy has been devoted to untangling questions of interpretation than connecting disciplines.

The primary purpose of this dissertation is to minimize these complexities and investigate the core combinatorial mechanisms that lie at the heart of linguistic compositionality. Specifically, we introduce a new neurolinguistic paradigm that uses magnetoencephalography (MEG) to measure neural activity during the processing of simple adjective-noun constructions (e.g. *red boat*). Despite consisting of merely two words, understanding such phrases still requires the fundamental ingredients of compositionality, namely the ability to productively construct a complex representation from simpler parts. The use of such minimal expressions allows for the isolation of neural signatures related to basic combinatorial linguistic mechanisms, and thus provides a foundation for grounding previous, more complex investigations and a clearer point of convergence for different disciplines.

After establishing the paradigm in the opening chapter, the remainder of the dissertation is devoted to investigating the scope of these basic combinatorial mechanisms across several domains. Within language, we first test their generality with respect to modality (auditory and visual stimuli; Chapter 2) and then broaden the investigation to both comprehension and production (Chapter 3). As few previous neurolinguistic studies have investigated combinatorial production mechanisms, this work represents a critical bridge between theoretical models of production and comprehension that, to date, have had scarce empirical connection. Finally, we explore the bounds of these combinatorial mechanisms both outside of normal grammatical expressions (Chapter 5) and outside of language itself, through two parallel minimal paradigms in the pictorial and mathematical domains (Chapter 4).

Chapter 1: Establishing the paradigm (published as Bemis & Pylkkänen, 2011, *J. Neuroscience*[5])

To date, the two pillars of neurolinguistic investigation have been complexity manipulations, in hemodynamic research, and expectation violations, in electrophysiological studies. In the former, increases in neural activity during the comprehension of various complex linguistic constructions, such as center embedding[6], *wh*-extraction[7], and scrambled verbal arguments[8], are assessed relative to simpler controls. In the latter, expectations regarding unfolding linguistic expressions are established by a preceding context and then modulations of neural activity are identified during the violation of these expectations compared to their fulfillment. Over time, different electrophysiological components have been associated with the violation of different types of expectations, such as of syntactic word categories[9], semantic associations[10], and syntactic structural expectations[4]. In both paradigms, the neural activity of interest is associated with exceptional, as opposed to normal, linguistic processing. Therefore, by design, the majority of past neurolinguistic investigations have been ill-suited to identify the neural correlates of basic combinatorial neural mechanisms. Even the relatively few experiments designed to measure neural activity generated during the processing of simpler stimuli have employed complete sentences, or even discourses, as their critical expressions[11, 12], thus making it difficult to confidently disentangle activity due to basic combinatorial processing from more complex mechanisms such as those required to store extended expressions in memory or resolve dependencies between separated linguistic items. Thus, to date, no clear paradigm exists for clearly isolating the combinatorial mechanisms that lie at the core of language's compositional power.

Thus, in the first experiment of the dissertation, we developed a paradigm specifically designed to address this goal and isolate the neural correlates of basic combinatorial linguistic mechanisms, unencumbered, to the largest extent possible, by complexity-driven operations. We leveraged the temporal resolution of MEG to isolate neural activity generated by the comprehension of a single object-denoting noun (*boat*). We then engaged combinatorial processing at this noun by presenting it after a simple color-denoting adjective (*red*). We contrasted this compositional context with a control that replaced the adjective with a length-matched non-pronounceable consonant string (*xhl*). In both cases, subjects were asked to judge whether a following picture of a colored shape matched the words that preceded it (Figure 1). We then only analyzed activity generated at the noun, which allowed us to assess the neural result of manipulating the presence of combinatorial processing while keeping the visual stimulus constant. To control for lexical differences in the context preceding the critical noun, we also had subjects complete an additional list task in which the adjectives were replaced by length-matched nouns (*cup*). In order to minimize combination between the resulting sequence of two nouns (a syntactically well-formed constituent in English), we chose unlikely noun combinations (*cup, boat*) and now asked subjects to determine if the following picture matched *any* of the words that preceded it, thus encouraging the maintenance of separate representations for each denoted object. Therefore, in sum, our paradigm presented subjects with four minimal, two-stimulus contexts, each containing identical critical items, for which we expected basic combinatorial processing to be present in the adjective-noun condition alone.

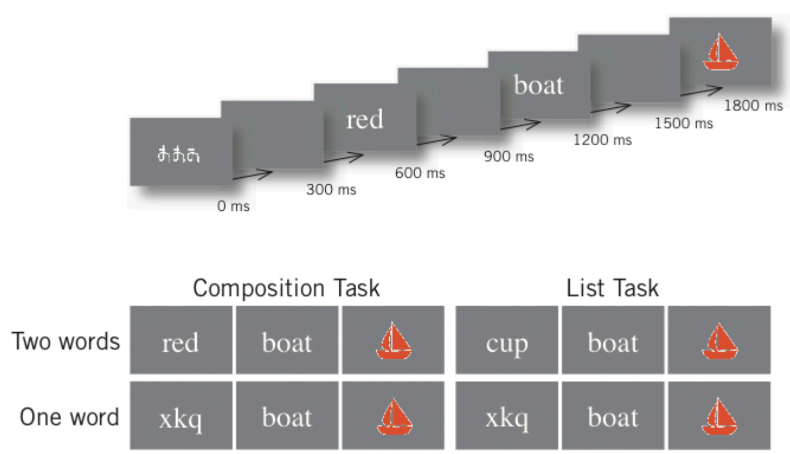

Figure 1: Linguistic experimental design. In each trial, participants indicated whether the target picture matched the preceding words. To satisfy this criterion, in the Composition task, *all* preceding words were required to match while in the List task, *any* matching word sufficed.

To characterize neural effects associated with this critical processing, we first estimated the cortical source of the magnetic fields measured during the processing of the critical stimuli and then used a non-parametric cluster-based test[13] to identify cortical regions that exhibited significantly increased activity during the combinatorial contexts compared to the controls. MEG source estimates (constructed for each subject from preprocessed condition averages) consist of a measure of estimated neural activity at hundreds of points distributed evenly across a smoothed cortical model, recorded at each millisecond during the presentation of the critical stimulus. In total, these measurements represent the pattern of activity that simultaneously explains the observed magnetic fields and minimizes the total power of the electrical current. To reduce the dimensionality of the data, our primary analysis investigated activity localized to five predefined regions of interest (ROIs) previously associated with combinatorial linguistic processing: two regions were drawn around the left and right anterior temporal lobes (lATL, rATL) to capture results linking increased hemodynamic activity in these regions to the processing of sentences compared to word lists[11, 14]; one ROI was centered on the ventro-medial prefrontal cortex (vmPFC), as several studies have indicated that MEG activity localized to this region correlates with semantic compositional processing[15, 16]; and two broad ROIs were included in the left inferior frontal gyrus (LIFG) and left posterior temporal lobe (lPTL) based upon a long history of neuroimaging and neurological studies indicating the importance of these regions to language processing in general[17, 18].

Our analysis revealed significant clusters of combinatorial activity in the lATL, at ~175-250ms, and in the vmPFC, at ~300-500ms (Figure 2). Activity in these regions at these times was significantly greater in the compositional adjective-noun condition compared to its one-word control and exhibited no difference between conditions in the list control. We observed a partially similar effect within the rATL, however, contrary to the lATL and vmPFC, activity in the one-word combinatorial control condition was the outlier in this ROI, exhibiting decreased activity relative to the other three conditions. Thus, the exact relation of this effect to combinatorial processing remains unclear. We observed no significant combinatorial activity in either the LIFG or lPTL ROIs. The only trace of such activity was observed in a subdivision of the lPTL encompassing the left angular gyrus (lAG). In this sub-region, a targeted test within the compositional task alone revealed a weak cluster of combinatorial activity concurrent with and partially preceding that in the lATL (~150-225ms). Supplementary full-brain and sensor-space analyses conformed closely to these ROI results and did not uncover any additional effects of interest.

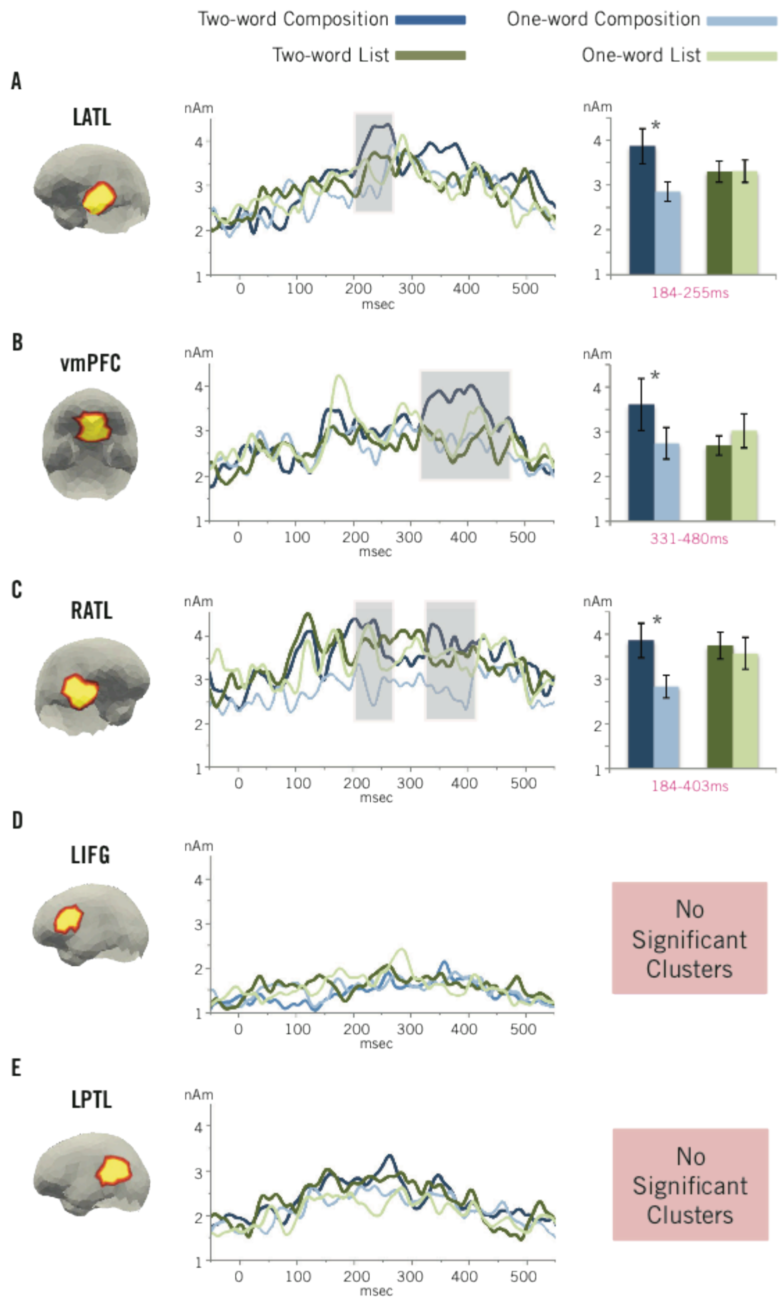

Figure 2: ROI results from the initial linguistic experiment. Gray areas denote significant combinatorial clusters of activity. $*p < 0.05$.

Thus, the initial experiment established the use of minimal two-word contexts as a viable method for investigating the neural underpinnings of basic combinatorial linguistic mechanisms. We identified significant combinatorial activity within the vmPFC and lATL during the composition of an adjective and a noun, suggesting that basic combinatorial operations may have driven previous results linking these regions to combinatorial processing in more complex paradigms[11, 15]. While the absence of such effects within canonical linguistic ROIs (the LIFG and lPTL) may have been due to factors often responsible for null results (low signal, noise, etc.), these absences are also consistent with established evidence that primarily links the lPTL to lexical processing[19, 20], which was controlled between conditions in the present manipulation, and the LIFG to the parsing of complex expressions[2, 21], which we did not employ. Though future work is required to disentangle the contributions of specific types of combinatorial operations (e.g. syntactic or semantic composition) to the effects observed in this initial experiment, compared to previous studies the present results reflect a drastically reduced space of possible operations and, therefore, a much simpler base from which to build.

Chapters 2 & 3: The linguistic domain (Ch. 2: published as Bemis & Pylkkänen, 2012, *Cerebral Cortex*[22]; Ch. 3: *submitted*)

The following two chapters are devoted to exploring the scope of basic combinatorial operations within the linguistic domain. In Chapter 2, the original paradigm is straightforwardly replicated within the visual and auditory modality. In Chapter 3, we adapt the design to production, providing the first direct neurolinguistic investigation into the temporal dynamics of basic combinatorial operations in this difficult-to-study domain.

Broadly speaking, the majority of past evidence suggests that, following initial perceptual processing, the comprehension of auditory and visual linguistic expressions share a common neural pathway[23-25]. We found further support for this evidence by administering the paradigm used in Chapter 1 in both the visual and auditory modalities to a single group of subjects. Our results (Figure 3) indicated not only that basic combinatorial neural mechanisms are shared between the two modalities, but that these mechanisms follow the same temporal ordering during both reading and listening. The localization of these effects was similar to that observed in the original experiment, but differed slightly. We again observed significant early combinatorial activity localized to the lATL. However, the clearest subsequent combinatorial effect now localized to the lAG, while combinatorial activity in the vmPFC was more muted. Though the exact reason behind this discrepancy is unclear, the lAG has been linked to combinatorial processing within other paradigms[14, 26], and we observed marginally significant combinatorial activity in this region in our original experiment. Regarding the weakened vmPFC effect, MEG is known to have low sensitivity to neural activity generated in this region[27], which may have contributed to increased noise – and therefore less observed combinatorial activity – in this region during this second experiment. While future work is needed to fully clarify this apparent reversal of significance for effects localized to the lAG and vmPFC ROIs, the present results reinforce the importance of the lATL in basic combinatorial processing and demonstrate the use of the new paradigm in exploring connections between different domains.

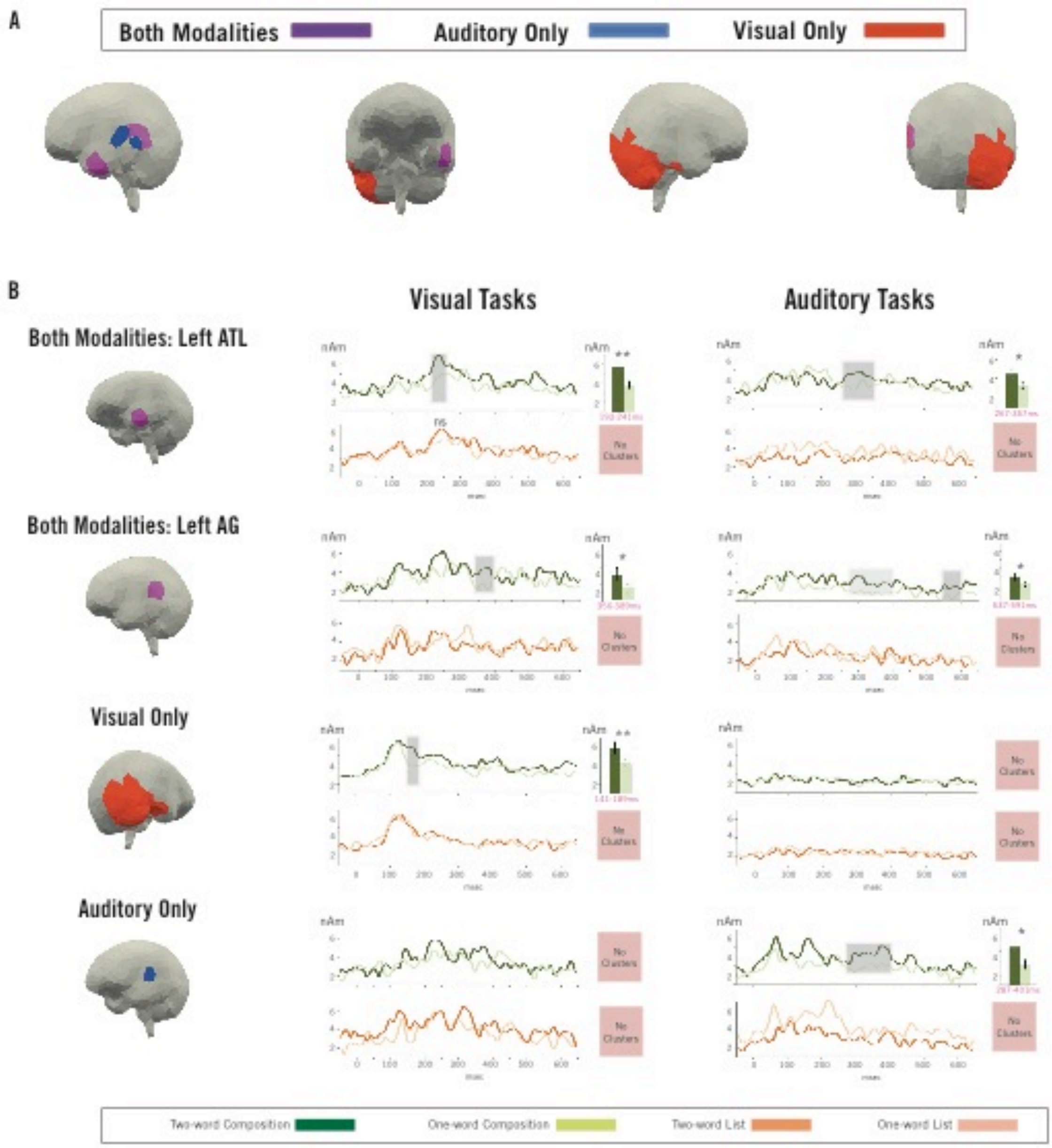

Figure 3: ROI results from the auditory-visual comparison. Gray areas denote significant clusters of combinatorial activity. *$p < 0.05$; **$p < 0.01$.

Our next experiment further extended this demonstration by entering the more complicated arena of language production. Across all fields of linguistic inquiry, production has been understudied relative to comprehension – a dichotomy most pronounced within neurolinguistics. Not only is it more difficult to elicit than deliver carefully controlled linguistic stimuli, but all measurements of neural activity are greatly confounded by the movement that accompanies speaking. Hemodynamic methods are less susceptible to this confound, and thus a nascent body of research is beginning to emerge from fMRI paradigms detailing the spatial distribution of cortical activity during combinatorial speech production[28-30]. Unfortunately, to date, the electrical activity and movement artifacts generated by the act of speaking have stymied electrophysiological investigations into multi-word, combinatorial productions, thus preventing any temporal characterization of these mechanisms. The only previous EEG paradigm to investigate simple phrase productions[31] failed to find any combinatorial effects; possibly due to their use of covert production[32] in an attempt to avoid movement confounds.

The simplicity of our design, however, provides an alternative method for minimizing these confounds. Past behavioral evidence indicates that during the production of simple adjective-noun phrases combinatorial semantic and syntactic processing is completed before articulation begins[33]. Thus, by simply reversing the logical structure of our paradigm, we were able to capture neural activity associated with these combinatorial processes before movement could contaminate the measurement. Specifically, we presented subjects with the target pictures from the original experiment and asked them to produce the corresponding adjective-noun description (Figure 4). We then analyzed the epoch immediately following the presentation of the picture, during which we expected the critical combinatorial processing to occur. The choice of a suitable control, however, was somewhat more complicated than for comprehension because naming latencies are significantly faster for single words compared to phrases[34]. Thus, the former is not a viable control for the latter as the faster responses in the control condition would then contaminate the analysis epoch. Naming latencies are also affected by phonological onset[35] and word frequency[36]. Therefore, to control for these factors we asked subjects to name two colors of a circular blob from left to right (Figure 4). This condition matches the phrases in terms of number of words produced, as well as the phonology and frequency of the initial word. Further, behavioral evidence indicates that in lists, as for phrases, lexical access for both items precedes articulation[37]. Thus we expected a contrast between the prearticulation periods of these conditions to reveal increased neural activity related to combinatorial processing in the phrase condition. We then used a separate control task to assess any effects due to perceptual differences between the two production prompt types (Figure 4).

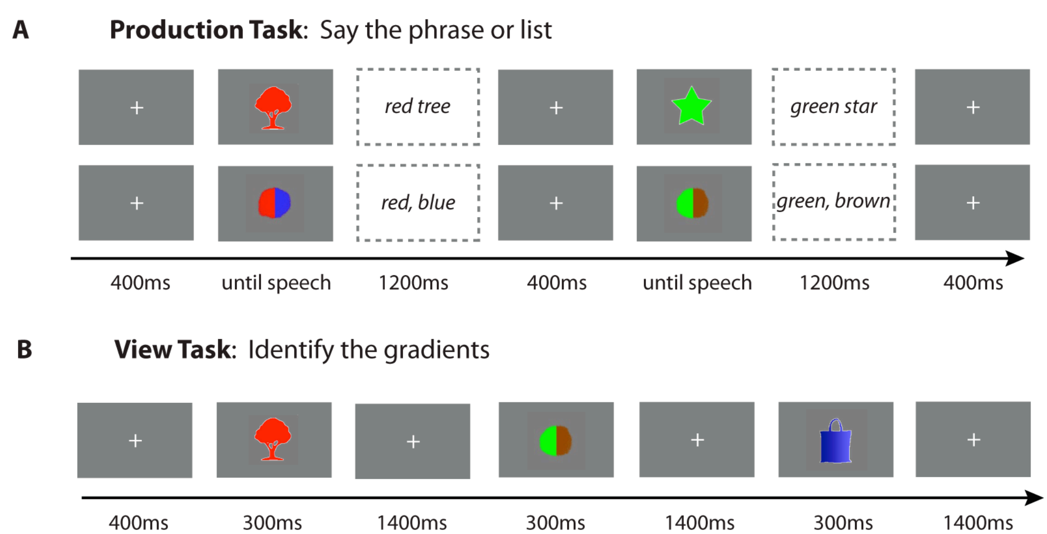

Figure 4: Experimental design for the production experiment. In the production task (A), subjects named either colored shapes ('red tree') or two colors of a circular blob from left to right ('red, blue'). In the control view task (B), subjects indicated if they detected a rare gradient on these same pictures.

The analysis for this experiment exactly replicated that of the original, as did the location of significant combinatorial effects. We observed highly significant and extended combinatorial activity localized to both the vmPFC and lATL during the production of phrases (Figure 5). Intriguingly, the temporal order of these effects mirrored that observed during comprehension, with combinatorial activity now beginning in the vmPFC, at ~185ms, followed by activity in the lATL, at ~250ms. These findings represent the first direct temporal mapping of combinatorial linguistic mechanisms during language production and provide evidence that combination initiates concurrent with lexical access, which single word studies place at ~175-250ms[38]. Further, the observed temporal reversal of combinatorial activity in the vmPFC and lATL compared to comprehension constitutes the first direct evidence of the long-held theoretical supposition[39, 40] that production and comprehension are, to some extent, mirror images of each other, utilizing a common neural pathway but in opposite directions.

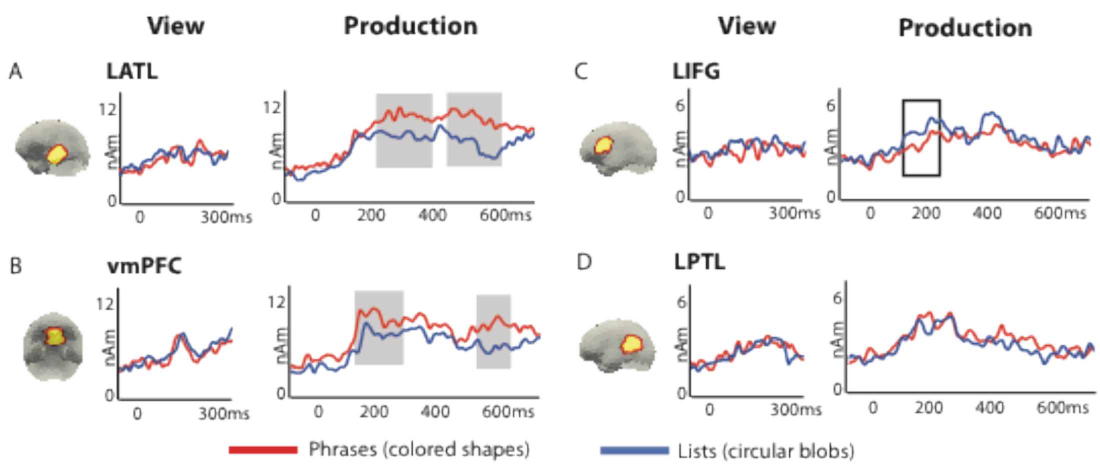

Figure 5: ROI results for the production experiment. Shaded regions indicate significantly greater activity during phrase productions while the boxed region indicates significantly increased activity during list productions.

Chapters 4 & 5: Testing the bounds (Ch. 4: published as Bemis & Pylkkänen, 2013, *Front. Psychology*[41]; Ch. 5: *under revision*)

While the two previous chapters demonstrate the malleability of the paradigm with respect to different facets of the linguistic domain, the final two chapters push the bounds beyond the normal operating domain of linguistic combinatorial mechanisms. Chapter 5 explores the flexibility and automaticity of these core processes by contrasting canonical adjective-noun phrases (*red boat*) with their non-canonical reversals (*boat red*). Space restrictions prevent a full description of this experiment, however, in brief, our results support past findings that indicate basic combinatorial operations are automatically engaged when processing canonical phrases[42, 43], and we find evidence that this engagement can be strategically initiated for non-canonical phrases in response to task demands.

Chapter 4 presents an explicit investigation into the domain-generality of basic linguistic combinatorial processes by adapting our linguistic paradigm to two non-linguistic domains – pictures and mathematical expressions. Though there exist many previous investigations into the domain-generality of linguistic processing, such studies have almost exclusively been modeled upon standard neurolinguistic paradigms, i.e. those that either manipulate complexity or violate expectations. Complexity manipulations using both linguistic and non-linguistic stimuli have been shown to modulate activity in the LIFG[2, 44], and nearly every canonical ERP effect associated with a linguistic violation has been elicited using non-linguistic paradigms as well[45-47]. While these results suggest that domain-general processes operate during language comprehension, they suffer from the same interpretational difficulties as the linguistic paradigms upon which they are modeled. Thus, it is not clear whether these shared effects reflect the domain-generality of basic combinatorial linguistic mechanisms or the use of more explicitly domain-general abilities, such as memory or selection processes.

To directly address this question, we first adapted our paradigm to the pictorial domain. Though much work has investigated the combinatorial perceptual processing that underlies the parsing of visual images[48, 49], little empirical evidence exists regarding combinatorial conceptual processing during picture viewing. While completely disentangling these two processes is difficult, our paradigm attempted to engage the latter by replacing the adjective-noun phrases of the linguistic experiment with their pictorial equivalent. Subjects were then again asked to judge this stimulus against a following test picture. To maximize conceptual processing and avoid simple perceptual matching between the two we used different exemplars of the same shape type for matching trials (Figure 6). As a control, we presented uncolored shape outlines on a colored background and asked subjects to determine if the following picture matched in shape alone. If constructing a complex conceptual representation from pictorial stimuli invokes the same combinatorial mechanisms as linguistic stimuli, then we would expect to observe neural effects similar to those observed during linguistic composition during the processing of the colored shapes compared to the outlines, for which no combination is required. Using the same analysis procedure and ROIs as for the linguistic paradigms, we indeed identified increased activity localized to the vmPFC during the processing of colored shapes compared to outlines (Figure 7). This result suggests that the linguistic combinatorial process subserved by this region is domain-general in nature and further, that this process is most likely semantic, as the pictorial stimuli used in this experiment do not obviously incorporate any syntactic structure. Though strong conclusions cannot be drawn from the lack of observable effects within the lAG and lATL, the results do support a general dichotomy found in the literature in which these regions are driven primarily by linguistic tasks[14, 50] while the vmPFC has more often been associated with non-linguistic functions[51, 52].

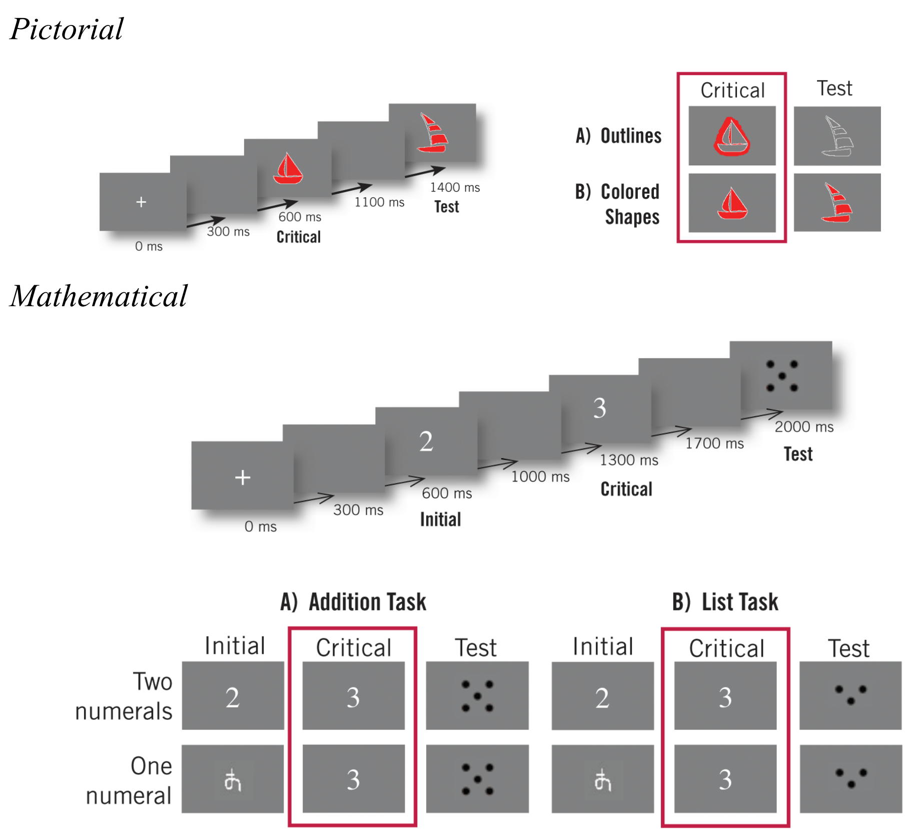

Figure 6: Experimental designs from the domain-generality experiment. In the *pictorial* experiment subjects first saw a critical shape (either a colored picture or an outline on a colored background) and were asked to judge if a following test shape matched the initial stimulus. On Outline trials **(A),** only the shape was required to match. On Colored Shape trials **(B),** both the color and shape were required to match. In the *mathematical* experiment subjects saw an initial stimulus (either a numeral, 1–5, or a non-sense symbol), a critical numeral (a numeral 1–5), and a test picture (a small set of dots). In the addition task **(A),** they were asked to judge if a following set of dots was equal to the sum of all preceding numbers. In the list task **(B),** they were asked to judge if the following set of dots matched any of the numbers.

Finally, we extended our linguistic paradigm to the mathematical domain, replacing the words with simple Arabic numerals. The logical structure of this experiment remained unchanged from the original experiment, however, in place of linguistic composition, we asked subjects to perform simple addition (Figure 6). Despite tantalizing similarities between the mathematical and linguistic domains, an increasing number of direct investigations have failed to uncover shared combinatorial neural activity between the two[53, 54]. Our experiment proved no exception. We did identify significant activity related to addition localized in the intra-parietal sulcus (IPS) – conforming to many previous results[55, 56] – but no significant effects were observed in any of our linguistic ROIs (Figure 7). This pattern of results demonstrates both the effectiveness of the paradigm outside of the language domain (by replicating the well-established IPS result) and also conforms to the hypothesis that effects within our linguistic experiments reflect specific compositional operations and not combination more generally.

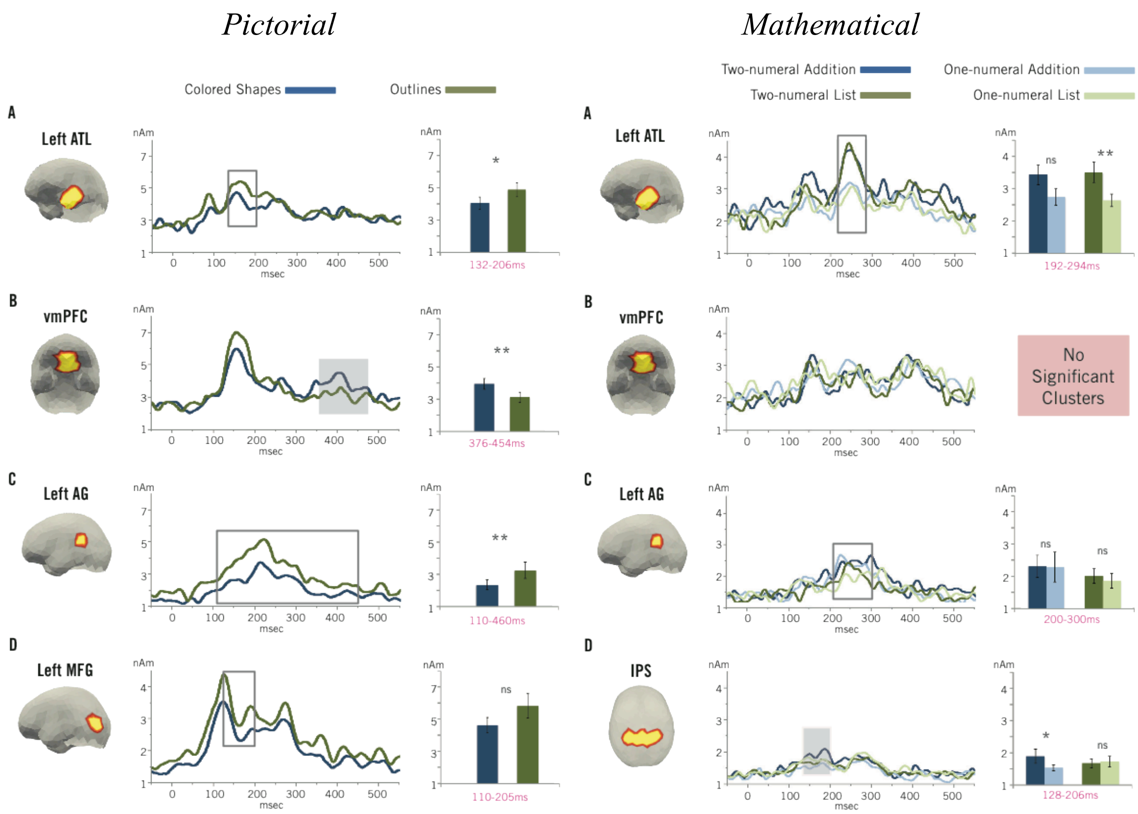

Figure 7: ROI results for the domain-generality experiment. Shaded regions represent clusters of significant combinatorial activity. Boxed regions represent significantly greater activity in the control condition. *$p < 0.05$; **$p < 0.01$.

Conclusion

The purpose of this dissertation was to establish a minimal paradigm for isolating the neural correlates of basic combinatorial linguistic mechanisms. By combining simple adjective-noun phrases with the spatial-temporal resolution of MEG, we were able to establish such a method and drastically reduce the functional space of the combinatorial mechanisms under investigation compared to previous studies reliant upon more complex stimuli. Further, the simplicity of the design lends itself well to adaptations across many domains. In this work, we demonstrated successful extensions both inside and outside of the language domain – connecting the visual and auditory modalities, beginning to build the missing empirical bridge between comprehension and production, and uncovering initial evidence for the domain-generality of basic linguistic combinatorial mechanisms. Thus, the present paradigm not only provides a method for driving straight to the heart of compositional language processing, but also furnishes an opportunity to directly connect linguistic investigations with a wide range of other disciplines and domains across cognitive science.

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