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Composition of event concepts: Evidence for distinct roles for the left and right anterior temporal lobes

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ABSTRACT

Characterizing the precise computations carried out by the various nodes of the semantic network remains a central challenge. One of the better understood nodes within this system is the left anterior temporal lobe (LATL), which shows an early (~250 ms) amplitude increase if the semantic composition between the current word and its context is in some ways "simple." As this type of effect has only been demonstrated for noun-modifier composition, we asked if a similar pattern is elicited for verb phrase composition. Agentive, resultative, and eventive adverbs were employed to vary whether the meaning of the adverb directly applies to the verb or not, with only eventives exemplifying direct and straightforward composition. Results showed that eventives, but not agentives or resultatives, elicited a significant increase in the LATL at 250 ms. The RATL showed a sharply contrasting pattern, with agentives showing the largest activity, suggesting a distinct role in semantic composition.

1. Introduction

1.1. Does the profile of LATL activity in noun phrase composition generalize to verbs?

Research on the brain basis of semantic processing implicates a broad network of regions distributed over the frontal, temporal, and parietal lobes (Binder, 2016; Fedorenko et al., 2016; Friederici, 2016; Humphries, Binder, Medler, & Liebenthal, 2007). How do these regions individually contribute to the many facets of sentence interpretation? For most regions, the answer is still elusive, but our understanding of the contribution of the left anterior temporal lobe (LATL) is beginning to be more detailed. In particular, the combined spatial and temporal resolution of magnetoencephalography (MEG) has enabled a focused study of specifically timed LATL activity in response to words in combinatory contexts. Accurate time resolution is crucial as without it, one might consider two effects the "same" even if they have very different time courses. The goal of the present study was to test whether a specific pattern of LATL effects that has been demonstrated for noun phrase composition also extends to verb phrase composition.

Composition related activity in the LATL peaks in MEG measurements at 200–250 ms after word onset (Bemis & Pylkkänen, 2011; and subsq.). Instead of syntactic or semantic composition in general terms, the activity appears to track a more conceptually driven process, sensitive to factors such as conceptual specificity (Westerlund & Pylkkänen, 2014; Zhang & Pylkkänen, 2015, 2018). Further, and most crucially for the current study, LATL composition also seems limited instances of composition that are computationally straightforward in the sense that no extra steps beyond lexical access are required for the two input items to combine. For example, while intersective adjective conjunctions, such as "the squares are *green and big*," elicit a LATL increase at *big*, which locally combines with *green* to create a set of entities that are both big and green, the effect is not observed for so-called collective interpretations of similar phrases (Poortman & Pylkkänen, 2016). A collective reading can be forced by choosing conjuncts that describe contradictory properties as in "the squares are *small and big*." Here, the local semantic combination of *small* and *big* fails, given the contradiction, and instead, an interpretation is derived in which *big* links back to *squares* to yield an interpretation in which some squares are big and others small, and none are both. Thus, plausibly, arriving at the collective interpretation is more complex than intersective composition, and only the latter drives the LATL.

A LATL effect specific to intersective composition was also observed in Ziegler and Pylkkänen (2016), who showed that although the LATL increases in amplitude when a relatively context-insensitive adjective such as *wooden* or *round* composes with a subsequent noun (as in

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wooden table), context-sensitive scalar adjectives such as *large* fail to do so. In the scalar case, the interpretation of the adjective crucially depends on the noun: *large* does not mean much unless we know "large for what?" Thus, for scalars, composition cannot proceed until the noun meaning is fully accessed, at which point the adjective meaning can also be determined. This is another situation in which LATL composition fails to operate. However, if the problem has to do with encountering a context-sensitive adjective without yet knowing the context, i.e, the noun, the difficulty should disappear if the context noun is encountered first. Then, the context for interpreting the adjective would be fully available at adjective onset. In fact, this is what happens, as shown both by the LATL effect for Poortman and Pylkkänen (2016) intersective adjective conjuncts (*the squares are green and big*) as well as by more recent data on English post-nominal modification and predication (Flick & Pylkkänen, 2018).

These results begin to paint a rather detailed picture of the brain's combinatory routines but so far, we do not know whether these patterns generalize across categories. To test this, we constructed a manipulation in the verbal domain in which composition could either proceed directly or required some additional steps beyond lexical access. Given that LATL composition has already been demonstrated for verb-argument composition (as in *eats meat*; Westerlund & Pylkkänen, 2014), we had reason to believe that in general, the LATL should engage for verb phrases. But whether it would show the same type of "anti-complexity" effect as we have observed for noun phrases remained unknown. Distinct neural substrates for verb and noun (or event and entity) processing have been proposed by several researchers (cf. Bedny, Caramazza, Grossman, Pascual-Leone, & Saxe, 2008; Boylan, Trueswell, & Thompson-Schill, 2015). Our study contributes to this literature by examining the composition process for verbs at a level of detail not characteristic of prior literature. To set up our manipulation, we took advantage of the varying properties of adverbs as verbal modifiers, a well-studied topic in linguistics.

1.2. Current study: Composition of verbs with different types of adverbs

Adverbial modification is different from adjectival modification in terms of both the grammatical and conceptual properties of the composing words. Nonetheless, semantic theories assume similar semantic representations for the adverbial modification of verbs and the adjectival modification of nouns (Davidson, 1967; Geuder, 2002; Parsons, 1990). For our study, this theoretical assumption provided a basis to expect the adverb + verb combination to engage the LATL in a comparable way as in the adjective + noun combination, despite their syntactic and semantic differences.

Our research question was whether the characteristic pattern of the LATL compositional activity at 200–300 ms is found in the verbal domain as well. In other words, would verb phrase composition also engage the LATL only if it is in some ways easy and direct? To address this, we manipulated whether an adverb *directly* composes with a following verb, by choosing three different types of adverbs: agentive, resultative, and eventive adverbs, based on the work of Geuder (2002). Geuder distinguishes genuinely manner-describing adverbs such as *slowly*, an "eventive" adverb, from adverbs whose meanings do not describe a manner per se, but rather *orient* to event participants such as the agent ("agentive adverbs") or the theme ("resultative adverbs"). For example, *reluctantly*, an agentive adverb, describes the state of an agent (i.e., *reluctantly paints* describes an event whose agent is reluctant). Similarly, *vividly*, a resultative adverb, describes the state of the theme that is created as a result of an action (e.g., *vividly paints* describes a painting event that results in a vivid picture). Crucially, the agentive and resultative adverbs, called *oriented adverbs*, are different from the eventive adverbs in that they are derived from an adjective that is inherently individual-describing (e.g., *reluctant*, *vivid*), whereas the eventive adverbs are derived from an event-describing adjective (e.g., *slow*). As an important consequence, the oriented adverbs compose with a verb in a non-direct way, as they do not modify the event named by the verb but instead predicate of an event argument. On the other hand, an eventive adverb is able to compose with a verb directly (e.g., *slowly paints* describes a painting event that is slow).

We used these three adverb classes as stimuli and hypothesized that only modification by eventive adverbs would evoke the early amplitude increase in the LATL, if the LATL combinatory response for verb phrases is indeed driven by the same underlying mechanism as for noun phrases. This was not a trivial assumption, however, considering that our stimuli involved composition of a conceptual entity that is a different kind than in the previous studies, i.e., event concepts as opposed to object concepts. A large body of literature has already shown how different types of concepts engage the brain differently; for example, the processing of an animal concept might engage left anterior temporal cortex whereas that of an action concept might engage the motor cortices or areas for motion processing (Bedny et al., 2008; Caramazza & Mahon, 2003; Hauk, Johnsrude, & Pulvermüller, 2004; Kemmerer, Castillo, Talavage, Patterson, & Wiley, 2008; Martin, 2007; Vigliocco, Vinson, Druks, Barber, & Cappa, 2011). If the function of the LATL is to integrate various features into a single, coherent conceptual representation, as assumed by the *hub-and-spoke model* which proposes a semantic hub that represents an amodal conceptual representation based on sensory information stored in respective sensory areas (Lambon Ralph, Sage, Jones, & Mayberry, 2010; Patterson, Nestor, & Rogers, 2007; Pobric, Jefferies, & Lambon Ralph, 2010), composition of different conceptual kinds involves different *spoke* regions (e.g., motor vs visual) and thus is likely to engage the LATL in a different way (cf. Mollo, Cornelissen, Millman, Ellis, & Jefferies, 2017). If this was the case, the same pattern of the LATL activity as in prior studies on noun phrase composition might not be found in our study.

A different, but closely related possibility was that the effect of event composition would localize to areas other than the LATL. Previous studies of event concepts or verb phrases have reported mixed results, sometimes implicating the left angular gyrus, or the left inferior frontal lobe, or the left anterior temporal lobe for verb phrase processing (Boylan et al., 2015; Shapiro, Moo, & Caramazza, 2006; Thompson et al., 2007; Westerlund, Kastner, Al Kaabi, & Pylkkänen, 2015). Considering this possibility, our analysis also included these candidate areas along with the LATL.

Finally, we expected the opposite pattern – participant-oriented adverbs driving *more* activity than non-oriented adverbs - to appear if the activity in our regions of interest reflected the difficulty of composition, or, amount of work to be done during the composition. In Poortman and Pylkkänen (2016), such a pattern was found in the right anterior temporal lobe (RATL); that is, the collective readings of conjoined adjectives elicited more activity in the RATL than intersective readings, whereas the LATL showed a reversed pattern. Thus, if the RATL is distinguished from the LATL in tracking the complexity of the semantic relation involved in composition, the same pattern could be observed for our stimuli as well.

All in all, our study aimed to assess whether the recent proposal that the activity of the LATL during 200–300 ms is signaling a "quick and easy" composition is tenable upon the inspection of other grammatical domains.

2. Methods

2.1. Participants

Twenty-six native English speakers aged 19–35 years old participated in the experiment. All participants were right-handed and had normal or corrected-to-normal vision. Prior to the experiment, participants completed a form giving their informed consent. A total of five participants were excluded during data analysis; two subjects' recordings were characterized by excessive noise, two subjects showed poor performance at the comprehension task (< 80% accuracy), and one

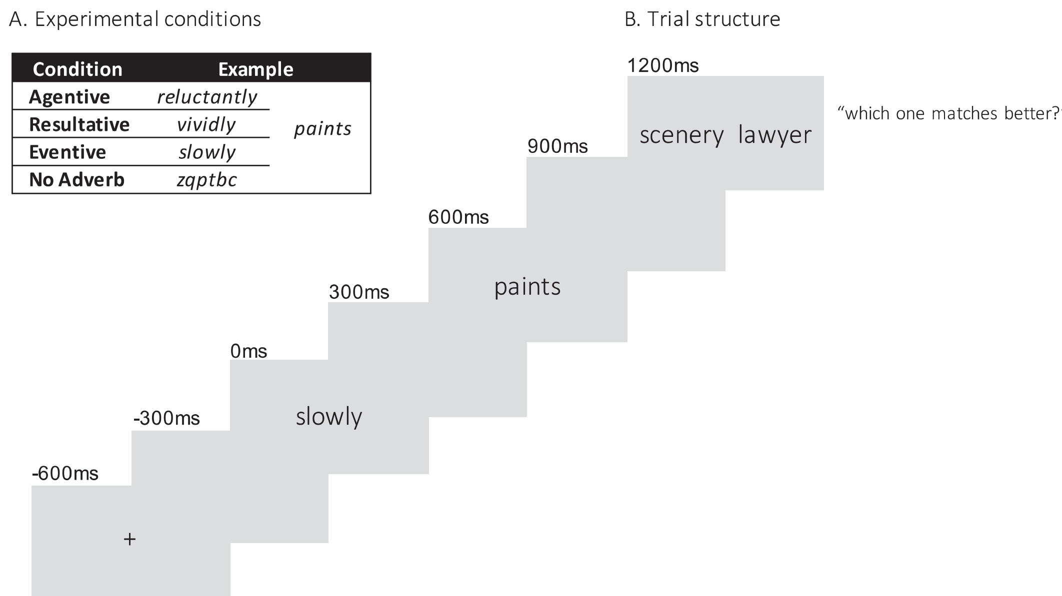

Fig. 1. Experimental conditions and trial structure. Every trial consisted of a fixation cross, two-word stimuli, and a comprehension task which remained on screen until the subject presses the button. Every screen lasted for 300 ms.

subject had a marker coil in an inaccurate position. This resulted in a total of twenty-one participants (13 females, a mean age = 24.7 years, SD = 4.1), eight of whom had structural MRIs.

2.2. Design and materials

We constructed four stimulus types by combining a verb with four different types of context items: eventive, agentive, and resultative adverbs as well as a non-pronounceable consonant string as a non-combinatory baseline condition (following Bemis & Pylkkänen, 2011, and subsequent work). In all conditions, the modifier always preceded the verb. The verbs were presented in the third person singular form as some verbs can be ambiguous with a noun in their bare form (e.g., *paint* can be a noun as well as a verb). All adverbs were derived from adjectives via the *–ly* suffix. The list of the verbs was the same across conditions, as shown in Fig. 1A.

Each condition had 62 verb phrases, which were made by pairing 31 different adverbs with two different verbs. For the No Adverb condition, we created 31 consonant strings via the random string generator at the English Lexicon Project website and paired each with two verbs, just as in the other conditions. As some of the adverbs ended up quite different from most of the adverbs in terms of their lexical properties such as length, frequency, or number of morphemes, our analysis targeted only a subset of trials, comprising of 50 verb phrases per condition, in which the lexical properties of the adverbs, i.e., length, number of morpheme, and log frequency, were matched across conditions (Table 1). In this subset, 25 adverbs were paired up with two different verbs.

2.3. Trial structure

As shown in Fig. 1B, a fixation cross first appeared in the center of the screen, and then an adverb and a verb appeared one at a time, with intervening blank screens between words. Every screen lasted 300 ms. To encourage full attention to the stimulus, a comprehension task appeared at the end of every stimulus. On the task screen, two nouns were presented side by side, and the subject chose the one whose meaning best fits the previously presented verb phrase. Among the two nouns, one noun was always better associated with the phrase, interpretable as a theme, agent, or instrument of the described event. For example, after the verb phrase *slowly paints*, the nouns *scenery* and *lawyer* were presented, from which *scenery* was supposed to be chosen given that *scenery* is a typical object of a painting event whereas no apparent association as such exists for a *lawyer*. Crucially, the semantic fit between (one of the) task nouns and the verb phrase was often subtle and required more than shallow processing. For example, after seeing a phrase *rapidly mixes*, *singer* and *cook* were given as two choices, and although *cook* is the right answer here, *cook* is not associated with the previous phrase in any superficial way. This way of selecting the task nouns was to enforce the participants as much as possible to fully access the meaning of the whole phrase, not just processing each word separately. All three noun types - theme, agent, instrument - were presented in equal numbers throughout the experiment.

2.4. Amazon Mechanical Turk norming study

Before the main experiment, we performed a separate norming experiment on Amazon Mechanical Turk to confirm that all of the adverbs in the stimuli are valid members of assigned category, i.e., agentive, eventive, and resultative adverbs.

Table 1
Lexical statistics of stimuli items. The three types of adverbs were controlled for major lexical properties such as length, log frequency, and number of morphemes, across conditions. Frequency data were from the Corpus of Contemporary American English (COCA) (Davies, 2008).

	Length	COCA log frequency	Number of morphemes
Agentive (N = 25)	Mean = 8.8, SD = 2.0	Mean = 3.1, SD = 0.7	Mean = 2.7, SD = 0.6
Resultative (N = 25)	Mean = 8.3, SD = 2.1	Mean = 3.0, SD = 0.7	Mean = 2.4, SD = 0.6
Eventive (N = 25)	Mean = 8.9, SD = 2.6	Mean = 3.3, SD = 0.9	Mean = 2.7, SD = 0.9
ANOVA p value	0.59	0.41	0.28

Table 2
Adverb norming: Test frames for the verb phrase (VP) paraphrase test on Amazon Mechanical Turk.

VP \ Paraphrase	**Agentive-test** The [Agent] was [Adj]	**Resultative-test** The [Theme] was [Adj]	**Eventive-test** The [Verb-ing] went [Adv]
Agentive (*reluctantly painted*)	**(1a) *The painter was reluctant***	(1b) *The picture was reluctant*	(1c) *The painting went reluctantly*
Resultative (*vividly painted*)	(2a) *The painter was vivid*	**(2b) *The picture was vivid***	(2c) *The painting went vividly*
Eventive (*slowly painted*)	(3a) *The painter was slow*	(3b) *The picture was slow*	**(3c) *The painting went slowly***

The design of the norming study was based on the notion that semantically distinct adverbs can be paraphrased in different ways. For example, a description of a painting event with a resultative adverb (e.g., *vividly painted*) can be paraphrased by having a potential object (e.g., *picture*) be predicated by the adjectival base of the adverb (i.e., *the picture was vivid*, (2b) in Table 2), whereas the same paraphrase may not work as well for the other two types of adverbs, i.e., (1b), (3b). Similarly, the verb phrase with an agentive adverb (e.g., *reluctantly painted*) can be paraphrased by having the agent (e.g., *painter*) be predicated of the adjectival base of the adverb in question i.e., (1a), whereas the same paraphrase is not as good for the other adverbs, i.e., (2a), (3a). Lastly, the description of a painting event using an eventive adverb (e.g., *slowly painted*) can be paraphrased into a construction that highlights the time course of the event using the *go* verb (e.g., *the painting went slowly*, i.e., (3c)). Again, this particular way of paraphrasing does not work as well for the other two adverbs, i.e., (1c), (2c). In Table 2, sentences in bold face are the best paraphrases for each adverb type.

Using Amazon Mechanical Turk, we tested whether the ratio of accepting each test frame as a natural paraphrase of a given verb phrase was significantly different depending on the adverb type. Each Turker was given 31 verb phrases, each of which was paired with one of the three possible paraphrases: e.g., *RELUCTANTLY PAINTED*, *The painting went reluctantly*. The verb phrases and paraphrases were all presented in the past tense so that they sound more natural. The Turker's task was to choose either Match or Mismatch depending on whether the paraphrase accurately described the meaning of the verb phrase. We expected that the percentage of choosing Match would be higher when the adverb was presented with the right type of test frame (i.e., the sentence in bold case in Table 2). Results were consistent with the intended interpretations (see Fig. 2). Paired-sample two-tailed t-tests showed that the percentage of MATCH response to the agentive adverbs was significantly higher for the agentive-test frame (69.71%) than for the resultative-test frame (24.23%) or the eventive-test frame (52.62%); agentive-test vs. resultative-test, $t(24) = 13.62$, $p < 0.01$, agentive-test vs. eventive-test, $t(24) = 6.86$, $p < 0.01$. Likewise, the percentage of MATCH response to the resultative adverbs was significantly higher for the resultative-test frame (81.42%) than for the agentive-test frame (29.58%) or eventive-test frame (43.56%); resultative-test vs. agentive-test, $t(24) = 16.07$, $p < 0.01$, resultative-test vs. eventive-test, $t(24) = 11.08$, $p < 0.01$. Finally, the percentage of MATCH response to the eventive adverbs was significantly higher for the eventive-test frame (72.72%) than for the agentive-test frame (54.82%) or the resultative-test frame (36.63%); eventive-test vs. agentive-test, $t(24) = 4.05$, $p < 0.01$, eventive-test vs. resultative-test, $t(24) = 6.52$, $p < 0.01$.

2.5. Procedure

Before the MEG recording, the head shapes of subjects were scanned using a Polhemus Fastscan three-dimensional laser digitizer. This scan included the positions of marker coils and anatomical landmark points, which will later be used for coregistration with MRIs. Then participants practiced the task with the experimenter in front of a computer outside the recording room. The stimuli were presented via PsychoPy (Peirce, 2010). The screen was about 50 cm above the subject's face, and the stimuli were presented in white Courier New font with a vertical visual angle of 0° 34′ against a grey background. The experiment consisted of eight blocks, each of which contained 32 trials. Blocks were pseudo-

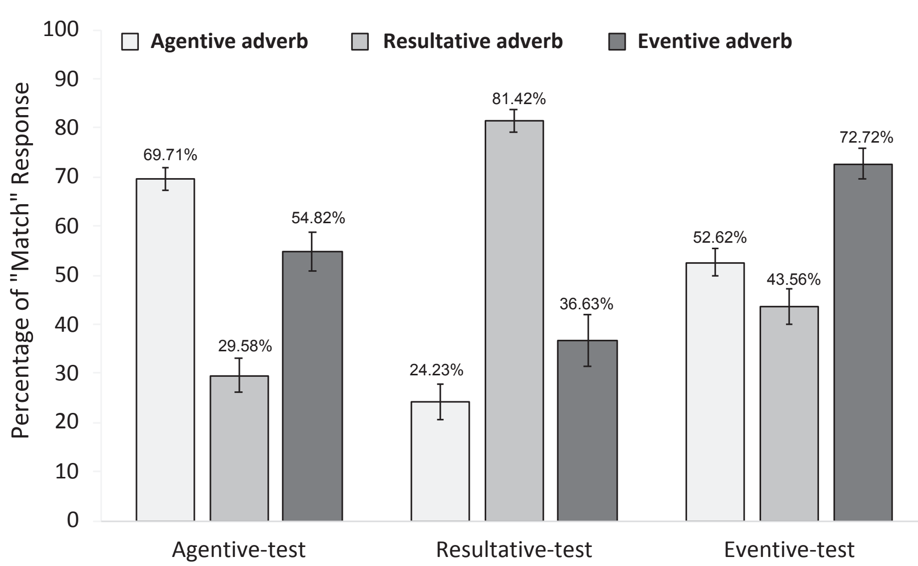

Fig. 2. The results of Amazon Mechanical Turk norming study. The y-axis shows the percentage of "match" responses, averaged across subjects. Error bar indicates standard error of mean.

randomized so that any given block contains equal number of trials from different conditions. Both the order of the blocks and the order of the items within each block were randomized. The average recording time was approximately 20 min.

2.6. Pre-processing of MEG data

Raw MEG data were collected using a whole-head 157-channel axial gradiometer system (Kanazawa Institute of Technology, Tokyo, Japan) with a sampling rate of 1000 Hz. To align the position of MEG sensors with subjects' actual head surfaces, digitized head shapes were coregistered with the FreeSurfer average brain (CorTechs Labs Inc., LaJolla, CA). For eight subjects who had a structural MRI scan, those scans were used instead. The MEG data were noise-reduced using MEG 160 software (Meg Laboratory 2.004A, Yokogawa Electric Corporation, Kanazawa Institute of Technology) that adopts Continuously Adjusted Least-Square Method (CALM) for noise reduction (Adachi, Shimogawara, Higuchi, Haruta, & Ochiai, 2001). The noise-reduced data were then low-pass filtered at 40 Hz and high-pass filtered at 1 Hz in MNE-Python (Gramfort et al., 2014). The high-pass filtering was necessary due to the high level of noise present in the data collected in New York City. Bad channels were removed by visual inspection and ICA was used to remove artifacts such as heartbeat and eye movements. The cleaned data were epoched from 200 ms before the onset of the first word to 600 ms after the onset of the second word; therefore, the total length of each epoch was 1400 ms. The first 200 ms formed the baseline in the calculation of the noise-covariance matrix. Epochs whose maximum amplitude exceeded 3000fT were rejected, resulting in a rejection of 3.38 trials per subject on average. MEG activities during the epochs were averaged per condition, and the forward solution was calculated using the Boundary Element Model (Bonnet, 1999; Mosher, Leahy, & Lewis, 1999) as the source model. Finally, the inverse solution, the activity at the source level, was computed by calculating the minimum-norm estimates (Hämäläinen & Ilmoniemi, 1994), using the free orientation of dipoles.

2.7. Data analysis

2.7.1. ROI analysis

Based on the literature that reports effects of combinatory processing in the left temporal lobe, our main ROIs included the left Brodmann Areas (BAs) 20, 21, and 38, which together covered most of the left temporal lobe. As our secondary ROIs, the right homologues of these regions were included, given prior evidence that the activity patterns of the right anterior temporal lobe may in fact positively correlate with complexity (Poortman & Pylkkänen, 2016). Left and right hemisphere ROI time courses were analyzed separately for the full design (FDR-correcting within hemisphere but not across; Genovese, Lazar, & Nichols, 2002), but for the combinatory conditions only, we also ran a bilateral analysis assessing the effect of adverb type across all left and right ROIs in a single analysis (corrected across all regions). To assess the effects of adverb type, we followed the nonparametric statistical procedures used in prior studies on LATL composition (Bemis & Pylkkänen, 2011; Westerlund & Pylkkänen, 2014; Zhang & Pylkkänen, 2015), evaluating the significance of an observed difference against a simulated null distribution that is created by repeated random shuffling of obtained data points (Maris & Oostenveld, 2007). Specifically, after activity was averaged across all the sources within an ROI for each time sample (= 1 ms), an F- statistic was calculated timepoint by timepoint and then these timepoints were grouped together into clusters whenever ten or more points maintained a p-value of less than 0.3 for at least 10 consecutive time points, as in prior studies (Bemis & Pylkkänen, 2011, 2013; Blanco-Elorrieta & Pylkkanen, 2016; Blanco-Elorrieta, Kastner, Emmorey, & Pylkkänen, 2018; Del Prato & Pylkkänen, 2014; Leiken & Pylkkänen, 2014; Poortman & Pylkkänen, 2016; Pylkkänen, Bemis, & Elorrieta, 2014; Westerlund & Pylkkänen, 2014; Ziegler & Pylkkänen, 2016). Among such clusters within the typical LATL time-window (200–300 ms), the cluster with the biggest F-value (i.e., the sum of the F-values at each time point within the cluster interval) was chosen, and the data points within that cluster went through 10,000 random permutations, randomly shuffling the condition labels within subjects. The statistical significance of the actual data was evaluated against this null distribution, its p-value being the proportion of the permutations whose statistic is greater than the observed statistic (corrected alpha = 0.05).

After ANOVA testing, pairwise *t*-tests were performed to test the presence of composition effects by comparing each of the combinatory conditions against the non-combinatory control. These t-tests were one-tailed, if performed on the left hemisphere data, given that combinatory conditions were always predicted to elicit more activity than the no adverb condition during the time interval of interest.

2.7.2. Analysis on the left angular gyrus and the left inferior frontal gyrus

In addition to the left and right ATL, we searched the left inferior frontal lobe and the left angular gyrus regions as well, the two regions that are usually considered to be part of a larger semantic network, asking whether the neural index of verb phrase composition is exclusively found in left temporal ROIs or not. We ran the temporal ANOVA test over the time courses between 100 and 400 ms (0 ms = onset of the second word) of the left angular gyrus (i.e., left BA 39 and 40) and the left inferior frontal lobe (i.e., left BA 44, 45, and 47), respectively.

3. Results

3.1. Behavioral results

The mean accuracy across all 21 participants and all conditions was 91.5% (SD = 4.1%). Proportion of accurate answers was not significantly different across conditions; $X^2(3) = 3.37$, $p = 0.3$. The mean response time for all conditions across 21 participants was 1.46 s (SD = 0.63 s), and there was no significant difference in response time across conditions; $F(3, 6388) = 0.91$, $p = 0.43$. Since the purpose of having a comprehension task was to make subjects pay full attention to the stimuli, the behavioral results were not further analyzed.

3.2. ROI results

A one-way ANOVA on the time courses of left BA 20, 21, and 38 revealed a reliable effect of adverb type in BA 38 at 280–296 ms ($p < 0.05$), driven by increased activity in the eventive condition (see Fig. 3A), though this cluster did not survive FDR correction across regions. Follow-up pairwise t-tests showed that the eventive condition elicited a significantly larger activity than no adverb condition ($p = 0.03$), while neither the agentive nor the resultative condition reliably diverged from no adverb condition, as shown in Fig. 3C.

Results from the right BA 20, 21, and 38 showed significant clusters in BA 21 ($p < 0.01$, 250–296 ms, FDR corr. across regions) and BA 38 ($p < 0.01$, 237–297 ms, FDR corr. across regions). In both of these regions, the agentive condition evoked the greatest activity during the significant clusters (Fig. 3B). Follow-up pairwise t-tests showed that in the right BA 21, the agentive condition elicited a significantly larger activity than both the eventive conditions ($p = 0.01$, 242–282 ms) and the resultative conditions ($p < 0.01$, 247–300 ms) (Fig. 3E). In the right BA 38, the agentive condition elicited a significantly larger activity than the resultative conditions ($p < 0.01$, 247–300 ms) (Fig. 3D). We also ran the same ANOVA test over a later time window, at 300 – 500 ms after the onset of the verb, and found no significant cluster in either ATL region.

Lastly, an ANOVA over the combinatory conditions, i.e., agentive, resultative, and eventive, with all six ROIs included (i.e., left BA 20/21/38 and right BA 20/21/38) revealed an effect of adverb type in all the

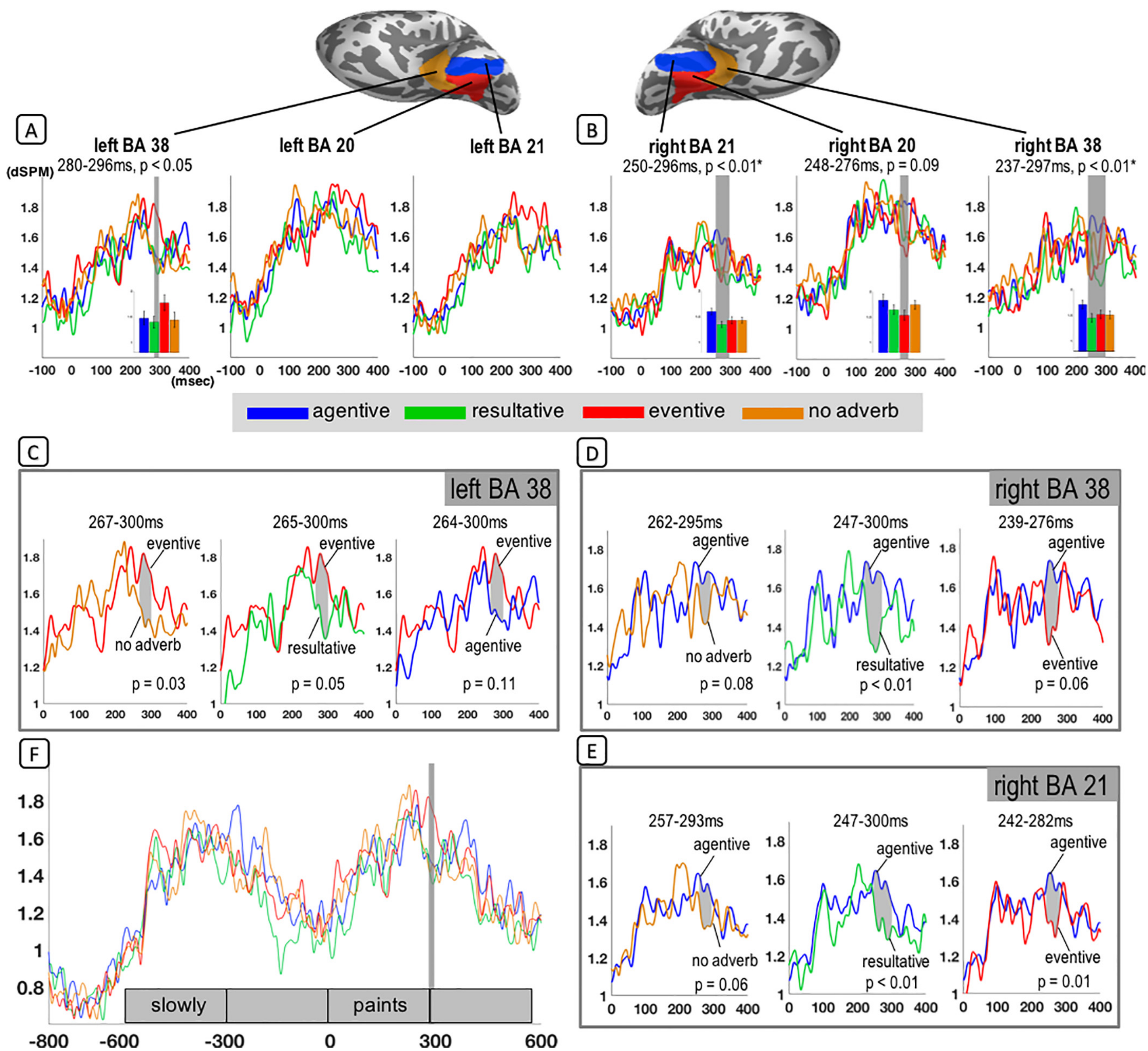

Fig. 3. ROI results for the left and right ATLs during the presentation of the second word (i.e., 0 ms = onset of the verb). (A, B) Significant clusters from ANOVA tests are shaded and the bar graphs below them show the averaged activity during each cluster. Error bar indicates SEM. Clusters that survive the correction for multiple comparison are marked with the *. (C, D, E) Pairwise comparisons from some of the ROIs. In the left BA 38 (C), the eventive condition elicits a larger activity than the other conditions. In the right BA 38 (D) and 21 (E), the agentive condition elicits a larger activity than the other conditions. The right BA 20 (not shown) showed the same pattern. (F) The time course of the brain activity in the left BA 38 during the entire epoch. (x-axis: msec, y-axis: dSPM).

ROIs except the right BA 20: left BA 20 ($p = 0.01$, 287–299 ms), left BA 21 ($p < 0.01$, 281–300 ms), left BA 38 ($p < 0.05$, 277–299 ms), right BA 21 ($p < 0.01$, 247–297 ms), right BA 38 ($p < 0.01$, 241–300 ms) (all significant after FDR correction across regions).

3.3. Results on the left angular gyrus and the left inferior temporal gyrus

ANOVA over the time courses between 100 and 400 ms (time-locked to the onset of the second word) in the left angular gyrus region found no significant ($p < 0.05$) clusters in either of the left BA 39 or BA 40. Likewise, the same ANOVA over the left inferior frontal area, i.e., the left BA 44, 45, and 47, did not find any significant clusters (Fig. 4).

4. Discussion

4.1. Evidence for similarity in composing complex event concepts and entity concepts

This study investigated the inner working of the brain's composition mechanism by asking whether verb phrases exhibit the same detailed patterns of combinatory activity in left anterior temporal cortex as have been reported for noun phrases (Poortman & Pylkkänen, 2016; Ziegler & Pylkkänen, 2016). Specifically, for nouns and their modifiers, composition effects in the LATL at 200–300 ms have been limited to very simple cases of composition, suggesting that this region may primarily perform rather context-insensitive conceptual combination. To test whether verbs and their modifiers pattern similarly, we examined the composition of adverb + verb combinations, varying the semantic type

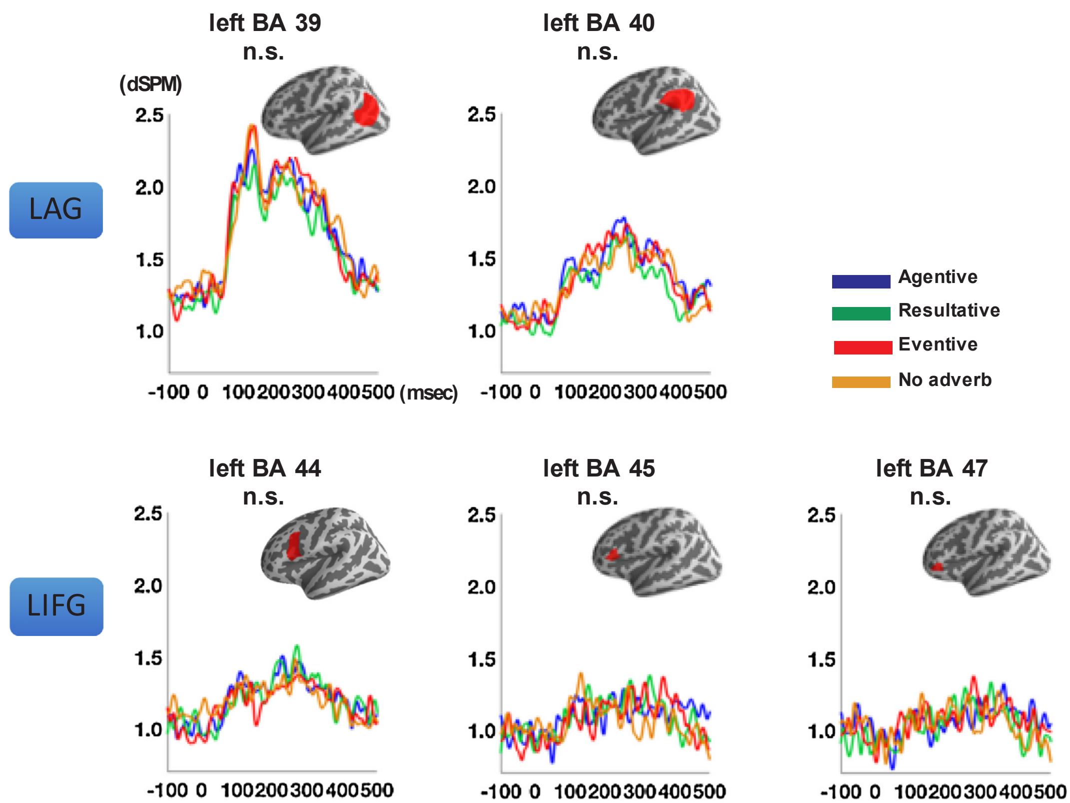

Fig. 4. Results from other potentially combinatorial regions such as the left angular gyrus (i.e., left BA 39/40) and the left inferior frontal cortex (i.e., left BA 44/45/47). No significant clusters were found at 100–400 ms after the onset of the second word.

of the adverbs such that the meaning of the adverb applied to the verb either directly, as exemplified by our eventive adverbs, or indirectly, as elicited by the agentive and resultative adverbs. Our results showed that only the direct combination of adverbs with verbs elicits increased activity in the LATL, which is qualitatively similar to the pattern reported previously for nouns. Thus our findings suggest uniformity for combinatory mechanisms in the verb and noun domains. Our results also conform to the hypothesis that semantic composition is a multi-stage process in which the compositional activity in the LATL at ~250 ms most likely signals one of the earliest stages (Ziegler & Pylkkänen, 2016).

4.2. Contrasting patterns of activity in LATL vs. RATL

In addition to the LATL results, we also observed a sharply distinct pattern in the right ATL. Specifically, the agentive condition elicited a significantly increased activity in the right BA 20, 21, and 38 at an overlapping time with the LATL effect. This clearly diverging pattern between the RATL and the LATL suggests that despite these two regions often showing similar effects (Bright, Moss, & Tyler, 2004; Pobric, Lambon Ralph, & Jefferies, 2009), they must contribute differently to semantic processing. Specifically, our results add to a growing body of research suggesting an important contribution of the right hemisphere in semantic processing (Federmeier, Wlotko, & Meyer, 2008; Jung-Beeman, 2005; Mitchell & Crow, 2005), and especially to studies reporting an engagement of the right hemisphere in situations in which more global processing of meaning is required. Specifically, the following conditions (but not limited to these) have been shown to engage the right hemisphere: (i) comprehension of a non-literal meaning such as idioms, metaphors, or humor (Bohrn, Altmann, & Jacobs, 2012; Bottini et al., 1994; Diaz, Barrett, & Hogstrom, 2011; Gainotti, 2016; Winner & Gardner, 1977), (ii) processing of discourse-level inference or coherence (Beeman, 1993; Kircher, Brammer, Tous Andreu, Williams, & McGuire, 2001; St George, Kutas, Martinez, & Sereno, 1999), (iii) semantic processing operating on weak and diffuse relations between meanings (Faust & Kahana, 2002; Jung-Beeman, 2005), and (iv) collective interpretations of conjunctions (e.g., *the hearts were small and big*, which calls for the construal of the global domain of entities necessary, i.e., entire set of hearts, among which some are small and some are big (Poortman & Pylkkänen, 2016). Taken together, these studies point toward the possibility that the right hemisphere is most likely recruited when a global aspect of a meaning needs to be processed, namely, the part of the meaning that should be sought outside the result of a strictly bottom-up composition of given inputs.

The precise nature of this global meaning computation still remains open. One possibility is that some type of late processing of the just presented adverb, as opposed to combinatorial processing, has elicited the increase in the RATL. For example, in prior ERP work, adjectives such as *fake* have elicit multiple stages of effects as compared to adjectives such as *flawed* (Schumacher, Brandt, & Weiland-Breckle, 2018). However, given the parallel timing and waveform shape with the LATL effect, what is perhaps more plausible is that the increase in the RATL may reflect some aspects of semantic composition, such as the activation of a hypothetical agent and subsequent predication of that agent by the adjectival root of the agentive adverb (e.g., *reluctantly paints* → *a painter is reluctant*). Such computations may have contributed to the increased activation in the right hemisphere during the verb presentation.

If the latter was the case, however, why would the resultative condition not have exhibited a similar right lateral increase? As the two types of adverbs were matched for major lexical properties such as length, number of morphemes, and log frequency, the observed difference is likely due to their semantic difference. Specifically, we suggest it may relate to the time at which a hypothetical argument noun (i.e., the agent noun in the case of agentive adverbs, and the theme noun in the case of resultative adverbs) can be postulated. That is, an agentive adverb may immediately allow the hypothetical agent to be activated and predicated of for some yet to be named event, because the property of an agent is largely independent of the action that follows (e.g., if a person *happily paints*, the person is in the state of happiness no matter what the action is). On the other hand, a result-oriented adverb would not activate a hypothetical theme argument as instantly as that, because the identity of the theme is dependent on the action named by the verb in a crucial way, as the theme is created *as a result of* the action; e.g., a painting event creates a picture as a result, whereas a describing event creates a description. Thus, crucially, at the adverb *vividly*, it is not as feasible to anticipate the theme noun in the absence of the verb, compared to the case of the agentive case. All in all, we hypothesize that the activation of the result noun and consequent predication of that noun by the preceding modifier does not occur as early as 200–300 ms in either of the ATLs.

5. Conclusion

While the left anterior temporal lobe has been implicated for combinatorial semantics in recent literature, its role in verb phrase composition has been relatively uncharacterized. Our study shows not only that the LATL is engaged in verb phrase composition, but also that its activity exhibits the same pattern as in noun phrase composition, such that an amplitude increase at ~250 ms is observed only for the context-insensitive type of composition. Put together, this suggests that the LATL can be characterized as a locus of a type of quick and easy conceptual composition across categories. A sharply distinct effect in similarly timed right-lateral activity suggests a right hemisphere contribution to more complex cases of conceptual combination.

6. Statement of significance

By combining MEG and an experimental manipulation motivated by formal semantic theory, this study advances our understanding of the semantic computation carried out by the left anterior temporal lobe, a central language area in most contemporary models.

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Appendix A

Adverb	Type	Agentive-test	Eventive-test	Resultative-test
angrily	Agentive	65.31	51.06	0.00
anxiously	Agentive	71.88	54.35	12.22
arrogantly	Agentive	61.70	31.91	31.25
attentively	Agentive	73.47	70.21	37.78
calmly	Agentive	67.44	66.00	18.00
carefully	Agentive	78.72	70.83	22.14
carelessly	Agentive	79.86	60.28	44.20
cautiously	Agentive	69.67	64.96	47.86
confidently	Agentive	67.35	53.06	16.00
desperately	Agentive	64.10	33.04	31.15
diligently	Agentive	91.43	60.84	44.29
excitedly	Agentive	54.00	53.33	4.26
gladly	Agentive	66.90	39.58	8.39
happily	Agentive	56.94	55.56	0.00
hurriedly	Agentive	95.56	76.60	51.06
meticulously	Agentive	78.57	72.03	57.02
nervously	Agentive	74.10	45.52	2.84
nonchalantly	Agentive	58.12	54.62	35.59
proudly	Agentive	78.15	31.93	9.65
reluctantly	Agentive	71.13	51.43	18.75
sadly	Agentive	41.55	38.57	25.35
tearily	Agentive	66.67	41.03	11.57
timidly	Agentive	72.73	53.19	53.19
tiredly	Agentive	72.03	54.62	4.13
willingly	Agentive	65.25	30.89	18.97
idly	Eventive	39.13	56.41	23.33
awkwardly	Eventive	38.95	78.02	29.90
deftly	Eventive	48.76	52.54	52.14
effortlessly	Eventive	52.59	95.69	95.00
gently	Eventive	65.22	66.67	13.33
gradually	Eventive	44.74	88.03	75.42
inefficiently	Eventive	76.52	61.34	34.96
intensely	Eventive	69.42	72.95	30.70
laboriously	Eventive	44.92	84.82	42.62
manually	Eventive	26.72	50.41	23.73
mechanically	Eventive	55.94	44.53	6.29
noisily	Eventive	83.74	83.47	14.66
progressively	Eventive	51.14	66.67	71.58
quietly	Eventive	58.82	79.14	11.49
rapidly	Eventive	71.23	90.85	24.46
rhythmically	Eventive	71.90	81.82	7.89
robotically	Eventive	70.45	57.45	78.72
routinely	Eventive	26.39	81.16	62.32
selectively	Eventive	72.27	51.33	39.83
sequentially	Eventive	37.61	87.39	75.65
slowly	Eventive	64.46	87.80	10.43
smoothly	Eventive	17.78	67.37	33.33

softly	Eventive	18.03	53.85	9.09
speedily	Eventive	84.17	88.14	11.97
swiftly	Eventive	79.71	90.21	36.81
cleanly	Resultative	13.70	58.57	69.29
coarsely	Resultative	22.31	35.59	64.35
colorfully	Resultative	36.96	36.17	88.04
correctly	Resultative	64.44	78.95	87.37
deeply	Resultative	7.83	57.02	91.45
defectively	Resultative	20.62	41.67	85.56
densely	Resultative	13.77	29.20	67.86
faintly	Resultative	15.96	17.89	70.21
finely	Resultative	14.43	13.54	56.99
firmly	Resultative	26.79	38.21	73.77
illegibly	Resultative	34.04	47.83	88.54
immaculately	Resultative	44.59	62.86	71.43
incorrectly	Resultative	57.02	61.40	84.03
indelibly	Resultative	31.91	40.86	89.36
intricately	Resultative	51.69	52.07	89.83
loosely	Resultative	12.50	32.63	81.44
messily	Resultative	56.74	58.99	98.56
neatly	Resultative	48.33	66.10	77.31
realistically	Resultative	44.79	39.56	94.79
seamlessly	Resultative	34.45	74.38	93.39
shallowly	Resultative	9.48	31.36	91.45
thickly	Resultative	22.38	16.90	88.97
thinly	Resultative	8.55	25.00	55.46
tightly	Resultative	15.60	36.88	86.33
vividly	Resultative	30.51	35.34	89.83

Appendix B. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bandl.2018.11.003.

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