MEG evidence for incremental sentence composition in the anterior temporal lobe: Supplementary material

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1. Region-of-interest background

This supplementary section reviews in more depth the literature relating to the ROIs that were investigated in addition to the left ATL: The left temporoparietal junction (TPJ), the ventro-medial prefrontal cortex (VMPFC), and the left inferior-frontal gyrus (IFG).

The left TPJ has shown sensitivity to the presence of phrase structure in a number of studies (e.g. Bemis & Pylkkänen, 2013; Humphries et al., 2006; Pallier et a., 2011). Previous studies have not converged on a clear understanding of this activation, though some researchers have linked activity along the posterior temporal axis not with basic compositional processes, but with assembling discourse-level representations (Humphries et al., 2006; Pallier et al., 2011; see also Ferstl et al., 2008), while others have linked posterior-dorsal activation with linear sequence-related processing (Bornkessel-Schlesewsky et al., 2015).

The VMPFC has also been associated with discourse- and text-comprehension (Maguire et al., 2001; Nathaniel-James and Frith, 2001; Kujala et al, 2007; Brennan & Pylkkänen 2012). At the sentence-level, studies have implicated this region in composing semantic representations (Pylkkänen & McElree 2007; Brennan & Pylkkänen 2008, 2010; Pylkkänen et al, 2008; see Pylkkänen et al., 2011 for a review and Hagoort & Indefrey, 2014 for a convergent meta-analysis). When comparing simple phrases to single words using MEG, Bemis & Pylkkänen (2011) found VMPFC activation for phrases to follow ATL activation by 100-150 ms, peaking around 400-500 ms after stimulus onset. This result is consistent with a stage of semantic composition in the VMPFC that is preceded by initial combinatoric processing in the ATL.

Lastly, sub-parts of the left IFG ("Broca's Area") have famously been implicated in various aspects of sentence comprehension. The functional roles of this region remain a matter of substantial debate (Rogalsky & Hickok 2010). Deficit/lesion research has linked damage in this region with difficulty comprehending complex sentences (Caramazza & Zurif 1976; Zurif, 1995), and in particular the comprehension of linguistic dependencies (Grodzinsky, 2000). Neuroimaging studies have also supported this functional hypothesis (Ben-Shachar et al., 2003, 2004; Caplan et al., 2008; Just et al., 1996; Stromswold et al., 1996). While some studies implicate working memory demands (e.g. Fiebach et al., 2005), others suggest that activation in this region may reflect, at least in part, computations specific to syntactic structure (Santi & Grodzinsky 2007a, 2007b, 2010; Zaccarella & Friederici, 2015). Precise localizations also vary across studies, with variability in the relative contributions of the pars triangularis (PTr) and pars opercularis (POp) (e.g. Santi & Grodzinsky 2007a,b). A second prominent hypothesis focuses on composition or unification operations involved at multiple levels of linguistic processing that form a posterior-anterior cline along the IFG (Snijders et al., 2009; Hagoort 2005, 2013). A related hypothesis links the PTr and POp with operations mapping from linear strings to different levels of structural and semantic representations (Bornkessel-Schlesewsky et al., 2012, 2015). Other studies report that the IFG is sensitive to selective attention to syntax (Dapretto & Bookheimer 1999; Embick et al., 2000; Hashimoto & Sakai 2002). Alongside these links to sentence-processing, left IFG has also been implicated in word-level processing such as lexical retrieval and the evaluation of lexical meaning in context (Bookheimer 2002; Bedny et al., 2007; Thompson-Schill et al., 1997; Hagoort et al., 2004). Thus, while the functional specificity of the PTr and POp is not yet known, evidence from numerous domains links them with both basic and more complex sentence-level operations.

2. Methods: MEG Procedure

2.1. MEG data collection

Participants lay prone in a dimly lit magnetically shielded room (Vacuumschmelze, GmbH) and viewed the stimuli on a screen centered 30 cm above their eyes. Participants were fitted with in-ear earphones (ER-3A; Etymotic Inc.) to receive instructions and they were monitored via speaker and video throughout the experiment. Prior to recording, each participant was fitted with five electromagnetic coils placed around the face to monitor head position. A 3D digitization (Fastscan; Polhemus, VT) was taken of location of these five coils, of three fiducial points (nasion, left pre-auricular, and right pre-auricular), and of each participant's head-shape.

The stimuli were presented word-by-word using Psyscope software (Cohen et al, 1993) in a grey font on a black background (courier, size 18) which subtended approximately 1° vertically and an average of 2.8° horizontally. Words appeared for 500 ms with a 300 ms inter-stimulus interval (ISI).

MEG signals were recorded continuously at 1000 Hz from 157 gradiometers (Kanazawa Institute of Technology, Kanazawa, Japan) with a 200 Hz low-pass filter

2.2. Source-space modeling

The source-space was a grid of three orthogonally-oriented dipoles spaced approximately 7 mm apart along the cortical sheet of the "fsaverage" template brain distributed with Freesurfer software (Martinos center, MGH, Boston). The template brain was aligned to each head-shape by minimizing the difference between head-shape points and template scalp. The template brain was then warped to conform to the head-shape for each participant using the Brainstorm toolbox in MATLAB (Tadel et al., 2011). Individual source-spaces were co-registered with the MEG array using the fiducial points.

Each participant's source model was calculated using a single-layer boundary element model (BEM) derived from the inner-skull boundary of the warped template (Hamalainen and Sarvas, 1989) and a noise covariance matrix calculated from the 100 ms baseline period preceding all stimulus items. Source activations were estimated by applying the *l2* inverse operator to each epoch and then dividing estimates by the predicted standard error to produce a dynamic statistical parametric map (dSPM; Dale et al., 2000). The root-mean-square of this value for each source-triplet was calculated and baseline corrected against a 100 ms pre-stimulus interval.

3. Auxiliary Analysis: Asynchronous Evaluation

3.1. Syntactic and semantic parsing

Several of the brain regions targeted in this study, including the ATL, have been implicated in semantic composition. For example, the literature has been divided as to whether the ATL involves building syntactic structure (Dronkers et al., 2004; Grodzinsky & Friederici, 2006), or performing semantic combinatorics (Vandenberghe et al, 2002; Stowe et al., 2005; Ferstl et al., 2008; Westerlund & Pylkkänen, 2014; Zhang & Pylkkänen, 2015; Blanco-Elorrieta & Pylkkänen, 2015). Evidence for the latter comes from multiple sources. Westerlund & Pylkkänen (2014) found increased LATL activation for two-word adjective-noun phrases only when the noun denoted a concept with low specificity (e.g. *bird,* in comparison to *sparrow*) (see also Zhang & Pylkkänen, 2015). Sensitivity to conceptual structure indicates a semantic, not syntactic function. This finding connects with research on semantic dementia that has shown a link between ATL atrophy and conceptual processing (Patterson et al., 2007) with greater impairment observed for more specific concepts (e.g. Warrington, 1975; Rogers et al, 2006, among others). Corroborative functional neuroimaging data have shown that activation in the LATL increases with conceptual specificity (Gauthier et al., 1997; Grabowski et al., 2001; Tyler et al., 2004). In contrast to these conceptual semantic effects, ATL atrophy has not been linked with syntactic deficits independently of semantic complexity (Wilson et al., 2014). In the context of this debate, we consider possible algorithmic differences between syntactic and semantic composition.

Considering semantic composition separately from syntactic parsing raises the possibility that multiple parsing strategies might be engaged simultaneously at different levels of analysis. In particular, semantic representations may be constructed asynchronously, at some delay, relative to syntactic composition (Shieber & Johnson, 1993). While the psycholinguistic data reviewed in the main text support a predictive left-corner parser, it does not necessarily follow that this parsing strategy would characterize all brain activity associated with sentence-level combinatorics. No prior research has tested whether syntactic and semantic compositional representations might dissociate during normal incremental comprehension. An initial hypothesis is that at any given word, the number of structure-building operations necessary to integrate the new word may be different than the number of semantic operations needed. This supplementary section reports on an analysis of the MEG data to test this hypothesis.

To illustrate this hypothesis, consider the partial phrase "Behind a stone…" The word "stone" is the first child of a noun phrase and under a left-corner strategy, would lead to the prediction of a subsequent head noun.[1] However, the interpretation of this noun phrase is not yet fixed (Kamp & Partee 1995). If the following noun is the word "house" then the noun phrase is interpreted by intersecting the meaning of "stone" with that of "house" (i.e. a thing which has the properties of being stone and being a house). On the other hand, if the following noun is "whale" then simple intersection is inadequate: assuming "living" is an essential property of being a whale, then the intersection of being stone with being a whale is null. We remain agnostic as to the alternative semantic compositional rules required here (see Kamp & Partee, 1995, for discussion); what is important is that the interpretation of "stone house" proceeds by different rules than the interpretation of "stone whale". Thus, a parser that posited a syntactic noun phrase given the adjective "stone" does not deterministically license the interpretation of that phrase. By virtue of the interpretive uncertainty highlighted here, semantic composition may be less predictive, and therefor delayed, compared with syntactic parsing.

Asymmetries between predictive syntactic and non-predictive semantic operations could occur at the beginning of a phrase where lexical items provide cues to the syntactic structure, but provide more limited guidance for semantic composition. The opposite pattern might occur near phrase endings when a word is integrated into a highly predictable syntactic context. The new word provides no additional information concerning the syntax, yet the word's meaning must be composed with the existing partial semantic representation. The broader pattern is one in which semantic composition might follow a bottom-up evaluation strategy, in contrast with predictive left-corner syntactic structure-building. Following Shieber & Johnson (1993), we dub the possibility of these asymmetries the "asynchronous evaluation" hypothesis. This hypothesis contrasts with a simple null hypothesis in which syntactic and semantic compositional operations occur synchronously.

Previous work that examines apparent mismatches between syntactic and semantic representations, so-called "coercion" phenomena, provide one piece of experimental evidence that supports distinguishing syntactic from semantic composition (see Pylkkänen et al., 2011 for a review). The asynchronous evaluation hypothesis offers a complementary approach to distinguish between compositional systems that can be applied when they are representationally homomorphic.

3.2. Modeling syntactic and semantic parsing asynchronously

The syntactic rules described in the main analysis were paired with a set of semantic composition rules. These context-free rules defined well-formed applications of compositional operations as in standard compositional semantic analyses (Heim and Kratzer, 1998). These semantic rules take syntactic structures as inputs and return

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[1] The string "behind a stone" may also form a complete phrase, of course. For the sake of illustration, it may be helpful to assume that factors such as context or intonation bias the parser towards treating the term "stone" as a modifier.

semantic objects. In all but two instances, the semantic rules were homomorphic to the corresponding syntactic rules.

The application of syntactic and semantic rules were woven together in a "non-pedestrian" algorithm (Stabler, 1991). "Pedestrian" describes an algorithm that completes one set of tasks before beginning the next set: in walking, one step must be taken before the next. In contrast, a non-pedestrian algorithm interweaves operations: when serving dinner, it is reasonable to serve the first dish while the main course is still in the oven, but it would be a mistake to wait until the entire dinner is prepared before serving anything at all. It is possible for both types of rules to be implemented synchronously; e.g. both could be applied according to a left-corner strategy. It is also possible, as discussed above, that syntactic rules could be applied more predictively than semantic composition rules. The asynchronous evaluation hypothesis was operationalized via the terms that must be recognized by the parser for a rule to be applied. This is called the "announcement point" by Demers (1977). Under standard left-corner parsing, the announcement point is set to follow the first term on the right-hand side of the rule (i.e. the first child). To realize the hypothesis that semantic composition may be delayed with respect to syntactic parsing, we set the announcement point for syntactic rules according to the left-corner strategy, while the announcement point for binary semantic followed the second term in accordance with a bottom-up strategy. As a consequence, semantic evaluation is bottom-up in a "local" sense, familiar from Fregean compositionality, in that interpretation of a mother node is a function of the daughter nodes that have been recognized. The non-pedestrian application of rules from different rule-sets means that the daughters that feed semantic interpretation may themselves dominate nodes that have not yet been recognized.

This inter-mixing of left-corner and bottom-up evaluation is a natural product of Stabler's non-pedestrian algorithm which is given as pseudo-code in (S1).

```
(S1) Given a set of lexical items L, a set of syntactic rules S, a
     set of semantic rules I, and a list T consisting of lexical
     items drawn from L,
     Where Word is a variable over lexical items,
     And moveOn is a boolean variable with an initial value of FALSE,
     For each Word in the input list T, moving from left to right,
       Until moveOn is TRUE
         If a rule from I can be applied, do so
         Else, if a rule from S can be applied, do so
         Else, add information for the lexical item in L that
           corresponds to Word and set moveOn to TRUE
       End Until
     End For
```

Operationalized in terms of alternative announcement points for syntactic and semantic rule-sets and implemented by the non-pedestrian algorithm, the left-corner strategy is conceptually linked with syntactic composition, and the bottom-up variant is conceptually linked with semantic composition. Under these parameter settings, the number of semantic rules diverges from the number of syntactic rules that are evaluated word-by-word, even for rules that are homomorphic (as are 25 of the 27 rules in the present grammatical fragment). Note that there are other possible ways to operationalize the asynchronous evaluation hypothesis, a point we return to in Supplementary Section

3.5. As in the main analysis, for a word *W* and a partial linguistic representation *C*, where the integration of *W* with *C* produces a representation *C*', the complexity associated with *W* was the number of syntactic or semantic rules that were applied to prove *C*' is well-formed. The analysis reported in the main text considers the bottom-up and top-down strategies separately from each other. Considering the two strategies together offers a way to test the asynchronous evaluation hypothesis as operationalized by the proposal that both left-corner and bottom-up strategies are simultaneously active.

3.3. Statistical analysis for testing asynchronous evaluation

We tested the asynchronous evaluation hypothesis by adding both left-corner and bottom-up predictors to the regression model simultaneously. By including both predictors, and residualizing them against each-other and other lower-level covariates, we test whether both parse step predictors independently and simultaneously contribute to characterizing the MEG data.

To account for correlations between the two parse steps predictors, the bottom-up predictor was residualized against word frequency, word length, and the left-corner rLC predictor. We dub this control predictor “crBU”. We then added crBU to a baseline model containing rLC and the other nuisance factors. By ordering the analysis in this way, we leverage the theoretical constraint that the left-corner “syntactic” parse step predictor would be logically prior to a bottom-up “semantic” parse step predictor.

In a control analysis, we entered the parse step predictors into the model in the reverse order. We residualized left-corner parse steps against rBU to create a “crLC” control predictor. This control predictor was then entered into a baseline model containing the rBU predictor along with other nuisance factors.

Table S1 shows pairwise correlations between the main parse step predictors, the control predictors just described, and the nuisance predictors described in the main text.

	rLC	*rBU*	*crLC*	*crBU*	*FRQ*	*LEN*	*ORD*	*POS*
rLC	1							
rBU	0.39	1						
crLC	0.92	0.00	1					
crBU	0.00	0.92	-0.39	1				
FRQ	0.00	0.00	0.00	0.00	1			
LEN	0.00	0.00	0.00	0.00	-0.73	1		
ORD	0.00	0.08	-0.03	0.08	0.03	-0.06	1	
POS	0.04	0.12	-0.01	0.12	0.02	0.00	0.06	1

Table S1: Pair-wise values for Pearson’s correlation coefficient between each numeric predictor entered into the regression models.

Note that without residualization, the two parse-step predictors are moderately correlated with each other (*r* = 0.39; row 2 column 1). The control predictors created via step-wise residualization (see row 4 column 1 and row 3 column 2) address the possibility that this correlation may confound interpretation of the regression results. In addition, FRQ and LEN show a familiarly high negative correlation with each other: shorter words are more frequent. While this correlation may lead to unstable estimates for the coefficients of these two terms, it has no bearing on the predictors that were the target of our analysis, which are uncorrelated, by residualization, with both of these factors.

3.4. Results for asynchronous evaluation

To evaluate whether the bottom-up and left-corner parse step predictors might make independent contributions, as predicted by the asynchronous evaluation hypothesis, we entered the crBU predictor into a baseline model with rLC parse steps and nuisance factors. There were no significant interactions between rcBU and block in the ATL or in any other region. Similar to the pattern observed for rBU in the main analysis, there was a significant main for rcBU in the ATL ($p < 0.05$). There was also a significant main effect in the VMPFC ($p < 0.05$) and marginally significant main effects in PTr ($p = 0.09$), POp ($p = 0.07$) and TPJ ($p = 0.09$). These findings do not support the asynchronous evaluation hypothesis.

We also conducted a control analysis in which we reversed the ordering between the left-corner and bottom-up parse step predictors. We used the crLC control predictor in which left-corner parse steps were evaluated after being residualized against the bottom-up predictor and low-level nuisance predictors. This analysis revealed the same patterns as described for rLC in the main text: a significant interaction between rcLC and block in the ATL ($p < 0.05$), and no interaction effects in any other region. This control analysis confirms that the order in which we tested our two parse step predictors does not materially change the pattern of results.

3.5. Discussion of asynchronous evaluation

In this auxiliary analysis we tested the asynchronous evaluation hypothesis that syntactic and semantic parsing operations might incrementally dissociate and independently correlate with distinct patterns of neural activity. We did not observe a significant interaction when bottom-up parse steps was residualized against left-corner parse steps in order to test whether it made an independent contribution. This null result holds for the ATL and for all other regions of interest that we tested. These results are inconsistent with our formulation of the asynchronous evaluation hypothesis.

Against this null result, an avenue for future work concerns the degree of (a)synchrony between syntactic and semantic parse steps: our model evaluated a fully bottom-up approach to semantic parsing, but a more granular approach would be to articulate different announce points (i.e. different degrees of predictiveness) on a rule-by-rule bases (cf. Hale, 2014). Doing so separately for syntactic and semantic rule sets would offer a more nuanced operationalization of the asynchronous evaluation hypothesis.

4. Grammar & Lexicon

4.1. Abbreviations

Semantic Rules

FA	Function Application
PM	Predicate Modification
ID	Identity
NA	No Analysis (excluded from parse step calculation)

Part of Speech Tags (POS)

P	Preposition
D	Determiner
Dpro	Pronoun
Dposs	Possessor
Q	Quantifier
num	Numeral
adv	Adverb
A	Adjective
N	Noun

4.2. Grammar

	Syntax	**Semantics**	**Semantic Rule**
1	PP -> P DP	[[P]]([[DP]])	FA
2	PP -> P	[[P]]	ID
3	PP -> P PP	[[P]]([[PP])	FA
4	DP -> D NP	[[D]]([[NP]])	FA
5	DP -> Dpro	[[Dpro]]	ID
6	DP -> Dposs	[[Dposs]]	ID
7	DP -> DP PossP	[[PossP]]([[DP]])	FA
8	DP -> Dposs NP	[[Dposs]]([[NP]])	FA
9	DP -> NP	[[NP]]	ID
10	DP -> D NumP	[[D]]([[NumP]])	FA
11	DP -> DP Conj DP	[[Con]]([[DP]])([[DP]])	FA x2
12	DP -> QP	[[QP]]	ID
13	NumP -> Num NP	[[Num]]([[NP]])	FA
14	QP -> Q NP	[[Q]]([[NP]])	FA
15	QP -> Q	[[Q]]	ID
16	QP -> Q* Num	NA	NA
17	PossP -> Dposs NP	[[Dposs]]([[NP]])	FA
18	NP -> NP PP	[[NP]][[PP]]	PM

19	NP -> AP NP	[[NP]][[AP]]	PM
20	NP -> N	[[N]]	ID
21	NP -> N N	NA	NA
22	NP -> NP LikeP	[[NP]][[LikeP]]	PM
23	NP -> NP conj NP	[[con]]([[NP]])([[NP]])	FA x2
24	AP -> A	[[A]]	ID
25	AP -> AdvP AP	[[AP]][[AdvP]]	PM
26	AdvP -> Adv	[[Adv]]	ID
27	LikeP -> Like DP	[[Like]]([[DP]])	FA

4.3. Lexicon

String	**POS**	**String**	**POS**	**String**	**POS**
ahead	P	he	Dpro	aspiring	A
around	P	her	Dpro	blocky	A
back	P	him	Dpro	cheerful	A
beside	P	it	Dpro	darkened	A
by	P	me	Dpro	dead	A
down	P	that	Dpro	dim	A
during	P	them	Dpro	elaborate	A
for	P	us	Dpro	elite	A
from	P			first	A
hear	P	her	Dposs	great	A
in	P	his	Dposs	half	A
into	P	my	Dposs	handcrafted	A
of	P	our	Dposs	herb-encrusted	A
on	P	s	Dposs	hiding	A
out	P			in-flight	A
over	P	all	Q	junior	A
through	P	only	Q	king-sized	A
to	P			large	A
until	P	like	like	lumpy	A
up	P			own	A
upon	P	four	num	pan-sized	A
with	P			prolonged	A
		and	conj	roomy	A
a	D			same	A
the	D	at	adv	shared	A
		least	adv	standup	A
he	Dpro	remarkably	adv	tear-stained	A
				united	A

String	POS
adolescence	N
aftershock	N
age	N
air	N
aisle	N
Americans	N
arm	N
armrest	N
bed	N
bottle	N
business	N
chainsaw	N
chicken	N
children	N
comic	N
death	N
dinner	N
earth	N
effort	N
elite	N
face	N
flagpole	N
flight	N
friends	N
funeral	N
generation	N
guilt	N
gurney	N
hands	N
happiness	N
high	N
hour	N
J.F.K.	N
joke	N
leg	N
life	N
light	N
magazine	N
mid-forties	N
minute	N
mirror	N
mitts	N
mother	N
mourning	N
mouths	N
movies	N
neglect	N
night	N
noses	N
parent	N
Paris	N
place	N
plane	N
Poland	N
profile	N
puddle	N
response	N
responsibility	N
rest	N
right	N
seat	N
seats	N
section	N
show	N
son	N
states	N
stoppers	N
table	N
theatre	N
time	N
top	N
trip	N
will	N
window	N
wood	N
years	N

5. Supplemental References

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