Increased Beta-Band Activity in the Active Maintenance of Fragile L2 Representations

Laurent Dekydtspotter, A. Kate Miller, Mike Iverson, Yanyu Xiong, Kyle Swanson, and Charlène Gilbert

Language processing appears to involve a cascade of processes occurring at different timescales in a network (Arnal & Giraud 2012; Giraud & Poeppel 2012; Hasson, Chen, & Honey, 2015; Lewis, Schoffelen, Schrieffers, & Bastiaansen, 2016; Lewis, Wang, & Bastiaansen, 2015). Partial representations must first be quickly generated on a short timescale in anticipation of structure. These representations need to be retained longer term for unification with what comes next in the input (Lewis et al., 2015; Lewis et al., 2016). Predictive brain processing seems to rely on the transfer of information from fast rhythms in the gamma band (25-100Hz) at/around 40Hz (Tallon-Baudry & Bertrand, 1999) to slow rhythms in the theta-band with oscillations from 4-7Hz (Hasson, et al., 2015). Additionally, the language network needs to maintain or change its processing mode as input imposes new demands. Beta-band activity (12.5-30Hz) has been tied to such monitoring (Lewis et al., 2015; Lewis et al., 2016). Crucially, oscillatory rhythms can be observed both in stimulus-induced responses and in stimulus-evoked responses, which reflect distinct neuronal activity. Induced oscillatory activity “…reflects functional changes in the parameters controlling dynamic interactions within and between brain structures” (Bastiaansen & Hagoort, 2003: 970), i.e. inter- and intra-modular communication. In contrast, evoked oscillatory activity reflects the “formation of a cell assembly” (Bastiaansen & Hagoort, 2003: 970) in the capture/characterization of input. In sentence processing, evoked activity therefore might reflect the activation of groupings of neurons in support of input capture - the generation of representations. In contrast, induced activity might reflect the coordination of information across distinct cognitive domains (Crocker, 1996). As a representation of the input is licensed by the grammar at different levels and information aligns across domain, commitment is induced to the current analysis.

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Indeed, parsing requires structure building and structure interpretation steps (Frazier & Fodor, 1978; Gorrell, 1995).

Native and non-native processing alike seems to engage a parsing reflex (Schwartz, 1987, 1999; Dekydtspotter & Renaud, 2014) supported by a dedicated language network (Fodor, 1983, 2000). However, non-native sentence parsing is also widely characterized as slower/more effortful (Juffs, 2005; Juffs & Harrington, 1995), or subject to delay (Boxell & Felser, 2017; Clahsen & Felser, 2018), decay (Dekydtspotter, Schwartz, & Sprouse, 2006), and fragility (Lim & Christianson, 2013) with weakly activated representations (Dekydtspotter & Miller, 2013) and reduced capacity (Hopp, 2010; López-Prego & Gabriele, 2014; McDonald, 2006; inter alia). The language processing system operating with later-acquired L1-based lexical representations might prioritize maintaining the continuous capture of input — without that, all is lost.

As a result, we propose that neuronal activity is best characterized in terms of a capture/commitment tradeoff (CCT). Parsing a non-native language requires neuronal effort devoted to input capture, which comes at the price of the amount of activity coordinating between processing nodes across the language network. This coordination enables commitment to structure through the congruence of information across domains. Trading off commitment for capture yields fragile structural representations that result in ‘good enough’ processing as the structural parse gives way to world knowledge (Christianson, Hollingworth, Halliwell, & Ferreira, 2001; Ferreira, Christianson, & Hollingworth, 2001; Ferreira & Patson, 2007; Lim & Christianson, 2013).

1. Background

Our investigation focuses on the processing at the bridge verb and subordinator (such as say that) in the context of wh-movement in French (1a, b).

(1a) Quelle décision le concernant est-ce que Paul a dit que Lydie avait rejetée sans hésitation?  
which decision him regarding is-it that Paul has said that Lydie had rejected without hesitation
‘Which decision regarding him did Paul say that Lydie had rejected without hesitation?’

(1b) Quelle décision à propos de lui est-ce que Paul a dit que Lydie avait rejetée sans hésitation?  
which decision at words of him is-it that Paul has said that Lydie had rejected without hesitation
‘Which decision about him did Paul say that Lydie had rejected without hesitation?’

The structure of the displaced wh-expression with either a modifier (Mod) structure (1a) or a complement (Comp) structure (1b) was manipulated to affect the nature of the structural predictions. Indeed, the Comp structure identified by à ‘at’ is lexically selected by the noun décision ‘decision’ and is intrinsic to its
relational interpretation. In contrast, the Mod structure is not selected. This distinction interacts with movements. Whether the displaced wh-expression includes a Mod le concernant ‘regarding him’ (1a) or a Comp à propos de lui ‘about him’ (1b) plays a role in wh-movement computations (Chierchia, 1995; Chomsky, 1995; Lebeaux, 1986; Freiden, 1988). The à marking indicates that a relational expression was selected from the lexicon. The noun in its relational interpretation must be present at every step of computation (1b’). In contrast, the Mod structure in (1a) need only qualify the noun phrase after all cycles of feature-driven computations have taken place, as indicated in (1a’):

\[(1a')\quad \text{[quelle décision le concernant [est-ce que [Paul a dit [< quelle décision> [que Lydie avait rejetée [< quelle décision sans hésitation]]]]]}
\]

\[(1b')\quad \text{[quelle décision à propos de lui [est-ce que [Paul; a dit [< quelle décision à propos de lui> [que Lydie avait rejetée [< quelle décision à propos de lui; sans hésitation]]]]]}
\]

In derivation (1b’), pronoun lui ‘him’ within the Comp structure is part of the syntactic chain. At the bridge between clauses, Paul constitutes a matching c-commanding expression as the relevant domain for binding lui ‘him’ is computed per binding condition B (Chomsky, 1986, 1988), as shown by the subscript in (1b’). No binding is immediately available with the Mod structure, however, as Paul never c-commands the pronoun in derivation (1a’). Thus, le and Paul must co-refer in discourse, each expression referring independently to the same individual.

We also manipulated whether an antecedent matched the pronoun in gender before bridge dit que (as in (1a, b)) or after it (2a, b). In (2a, b) the sentence processor also seeks an anaphoric interpretation for le and lui ‘him’ as soon as possible. This requires anticipation. Feature mismatch with feminine Lydie prevents binding or coreference and delays the establishment of an anaphoric dependency until the embedded clause. Still, because the parser actively anticipates syntactic dependencies (Dekydspotter & Seo, 2016; Omaki, Lau, Davidson White, Dakan, Apple, & Phillips, 2015), the Comp structure allows the anticipation of a structurally interpreted bound variable in the anaphoric interpretation of the pronoun in (2b). Binding relieves the need to actively maintain a discourse referent. Hence, in processing (2b) with a Comp structure, the parser anticipates not only an embedded clause but also a binding construal, as a function of grammatical design in which dependencies are resolved at the lowest level of structure (Reuland, 2001). Such design limits interpretation costs. In contrast, a binding computation is not automatically licensed in processing the Mod structure in (2a); an unresolved discourse referent for lui needs to be

\[\text{1 In the French interrogatives (1a) and (1b), the masculine pronouns le ‘him’ in (1a) and lui ‘him’ in (1b) are naturally construed with Paul, so that (1a) is typically synonymous with (1b). Indeed, 16 advanced NNSs (with English as their native language) and 16 NSs of French accepted the construal of lui and le with the matrix-clause subject at similarly high rates for Comps and Mods (NNSs: 96%/96%; NSs: 91%/89%).} \]
maintained. The processing should thus reflect the structure of *wh*-expressions: Mod structures should induce greater load than Comp structures.

(2a) *Quelle décision le concernant est-ce que Lydie a dit que Paul* which decision him regarding is-it that Lydie has said that Paul *avait rejetée sans hésitation?* had rejected without hesitation

‘Which decision regarding him did Lydie say that Paul had rejected without hesitation?’

(2b) *Quelle décision à propos de lui est-ce que Lydie a dit que Paul* which decision at words of him is-it that Lydie has said that Paul *avait rejetée sans hésitation?* had rejected without hesitation

‘Which decision about him did Lydie say that Paul had rejected without hesitation?’

Linguistic theory argues that the bridge between clauses constitutes a central computational step in recursive *wh*-movement (Barss, 2001; Lasnik, 2001). Psycholinguistic evidence indeed shows that clause boundaries in recursion refresh displaced expressions, enabling faster integration at gap sites (Gibson & Warren, 2004). From the point of view of memory, at bridge verb *dit ‘said’,* an embedded-clause dependency needs to quickly be predicted. This prediction takes the form of a partial representation that must then be retained in memory, so that it can be unified with the input coming next. The subordinator confirms an embedded-clause dependency. Predictive generation in the gamma rhythm (25-40Hz) and information unification in the slow theta rhythm (4-7Hz) presumably constitute a primary reflex across the native vs. non-native distinction.

On CCT, parsing non-native input would require greater investment into input capture. This distinctive neuro-processing mode results in greater Mod-Comp differences in evoked power for NNSs than for NSs. This bias is plausibly dictated by computational need, because all is lost if the input cannot be captured. Expense on the capture of input might trade off with maintaining dynamic links between brain substructures. Weaker coordination between processing nodes would result in fragile processing given that the congruence of information across linguistic domains, and ultimately comprehension, rely on coordination.

2. The Study
2.1. Research Questions

We ask the following research questions (RQs):

RQ1. Do we find distinct rhythms for neuro-prediction at the bridge verb and information unification at the subordinator in both NSs and NNSs?

RQ2. Do we find evidence of information transfer across neuronal actors in the network?
RQ3. Do we find NS-NNS distinctions in the activation of the language network at distinct rhythms consistent with CCT?

2.2. Stimuli and Methods

Critical stimuli were 25 quadruples on a 2 x 2 design (structure: Mod/Comp * antecedent: main clause gender match/mismatch) as in (3a-d).

(3a) *Quelle décision **le concernant** est-ce que Paul a dit que Lydie avait rejetée sans hésitation?
(3b) *Quelle décision **à propos de lui** est-ce que Paul a dit que Lydie avait rejetée sans hésitation?
(3c) *Quelle décision **le concernant** est-ce que Lydie a dit que Paul avait rejetée sans hésitation?
(3d) *Quelle décision **à propos de lui** est-ce que Lydie a dit que Paul avait rejetée sans hésitation?

‘Which decision regarding/about him did Paul/Lydie say that Lydie/Paul had rejected without hesitation?’

Mod-Comp differences are expected in anaphoric processing, especially as the Comp structure relieves the processing load associated with unresolved pronominal dependencies. We therefore focus on Mod-Comp differences in match vs. mismatch ([[(3a)-(3b)]->(3c)-(3d)]).

E-prime (Psychology Software Tools, Inc., 2016) delivered the stimuli word by word at the center of the screen in four blocks presented in random order, with stimuli ordered randomly within each block. Subjects sat approximately four feet from the screen. A fixation point at the center of the screen preceded each item for 700ms. Each word appeared for 300ms followed by a 250ms blank slide. Two-thirds of stimulus items were followed by true-false comprehension statements, which subjects had to respond to within 3500ms. Some of these statements examined the propensity for an anaphoric construal, while others queried other aspects of the sentences.

2.3. Participants and Testing Procedures

We report results from 24 NSs of French, including 4 left-handed individuals, as well as 22 NNSs of French, including 1 left-handed person. After providing biographical information, participants completed a C-test (Renaud, 2010) as a proficiency measure and the EEG task, each of the four blocks lasting 13 minutes. Breaks were included between blocks to ensure that the subjects stayed engaged.

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2 We decided not to exclude respondents because of handedness, as it has been shown that it is not left handedness per se but rather familial sinistrality that seems to influence brain patterns (Grey, Tanner, & van Hell, 2017), a factor that cannot reliably be tracked. However, because cyclic movement constitutes a basic property of grammar, effects of reconstruction could be expected across groups and the range of individual variation.
The 22 NNSs of French (average age = 29.1) began acquiring French during secondary schooling or later. These participants were students in the US at time of testing but had spent time abroad, with an average total length of stay of 1.1 years. C-test scores (average 45.5/50; range 33-50) clearly indicated that they were well above intermediate-level proficiency: Scores typically range from around 25 points for low intermediates (second semester) to 30 points for high intermediate learners (fourth semester). The 24 NSs of French (average age = 26.6) were also tested in the US, and they had, on average, lived abroad for 2.4 years. The average C-test score was 48.7/50, with a range from 45-50. Bilingual experience is therefore a constant across the population.

2.4. EEG Procedures

EEG was recorded with a 1000Hz sampling rate via a 64-electrode EGI system (Electrical Geodesics Inc., Eugene, OR) referenced to Cz during recording. The signal was amplified on a Net Amps 300 amplifier with a gain of 5000 and recorded by Netstation (version 4.5.4). Impedances were verified to be below 50 kΩ before each block. All preprocessing and data cleaning procedures were performed using the EEGLAB toolbox (Delorme & Makeig, 2004). Data were filtered offline with a .05-100.5-Hertz band-pass filter (0.1Hz transition bandwidth, -6 dB attenuation at cutoff frequency, Hamming windowed, order 33000). Line noise was removed using the CleanLine plugin for EEGLAB (Mullen, 2012). The data were then divided into 5.2-second epochs starting with est-ce que, the question marker, and running to the end of the stimulus. Bad channels were removed according to visual inspection with the TrimOutlier plugin (Lee & Miyakoshi, 2014). Epochs containing large artifacts were removed by the experimenters, with an average of 87% of trials retained across subjects. All participants indicated above had less than 10% bad channels and 30% bad epochs. Blinks, ocular movements, and EMG were removed from the recording using Independent Component Analysis. Data were re-referenced to average mastoids. All remaining trials were included in analyses because processing during the sentence is independent of behavior on comprehension checks.

2.5. Time-Frequency Analysis

Time-frequency analysis was applied to a 1.85 second epoch containing dit que ‘said that’ plus a 700ms pre-phrase baseline for both NSs and NNSs. A 50ms interval was left between the baseline and epochs to prevent power leakage in plotting. Each epoch was down-sampled to 200Hz (Luck, 2014). A family of Morlet wavelets with a width of 7 cycles was multiplied with the spectrum of the raw data from 1 to 40 Hz by using the FieldTrip toolbox (Oostenveld, Fries, Maris, & Schoffelen, 2011). The length of the wavelets is 3 standard deviations of the Gaussian kernel. At 1 Hz, the wavelet duration is 3.34 seconds and the spectral bandwidth is 0.43 Hz. At 40 Hz, the wavelet duration is 0.0836 sec and the spectral bandwidth is 17.14 Hz. The constraint on time resolution allows us to
only report data starting at 5Hz. Given our interest in the gamma, beta, and theta bands, the choice of 7 cycles in the usual 3-10 range seems to be the best time-frequency trade-off for an investigation from 5-40Hz. The power of the signal in each frequency is calculated as the square of signal amplitude. The same wavelet analysis was applied to both the evoked and induced power, the latter of which was obtained by subtracting the ERP power from the total power.

Although we seek power differences between groups and across conditions in the gamma, theta, and beta rhythms, the exact frequency of power differences and their spatial locations are a priori unknown. Consequently, cluster-based nonparametric permutation tests (Maris & Oostenveld, 2007) were performed in 1Hz steps from 1-40Hz. In preparation for statistical analysis for this mixed design, we first calculated the Mod-Comp power differences for the antecedent match [(3a)-(3b)] and mismatch [(3c)-(3d)] levels of the Mod-Comp factor for NSs and NNSs. Cluster-based \( t \)-tests with Monte Carlo randomization of 1000 times were performed for each time-frequency bin in the time window of 250-550ms at the group level. For main effects of the Mod-Comp factor, we compared power differences between antecedent match [(3a)-(3b)] and mismatch [(3c)-(3d)] levels of the Mod-Comp factor across groups using dependent-samples \( t \)-tests. For the main effect of group, we compared NSs and NNSs across the antecedent match [(3a)-(3b)] and antecedent mismatch [(3c)-(3d)] levels of the Mod-Comp factor using independent-samples \( t \)-tests. Following procedures specified in the FieldTrip toolbox for examining a possible interaction of condition with group, we first calculated the difference between the two levels of the Mod-Comp factor \([(3a)-(3b)]-[(3c)-(3d)]\) for each group. A permutation \( t \)-test was then performed on this difference of differences using independent-samples \( t \)-tests. For each critical word, contiguous frequencies with significant clusters were combined in each band and statistics are reported at these frequencies for the 250-550ms window. Follow-up ANOVAs were performed on average power for the resulting time periods and clusters to analyze the simple effects in interactions.

3. Results

Results of statistical analyses are reported in Tables 1 and 2. Only effects lasting over 100ms are discussed as theoretically relevant. In evoked power, a population-wide effect of Mod-Comp power differences in antecedent match vs. mismatch, indicating greater Mod-Comp differences in antecedent mismatch than in antecedent match \([(3a)-(3b)]<[(3c)-(3d)]\), started 394ms into the presentation of \textit{dit} ‘said’ and lasted 104ms from 34-40Hz (gamma rhythm; Table 1). It occurred over the right anterior scalp. A second population-wide effect at 6Hz (theta rhythm) in evoked power also revealed greater Mod-Comp ERP power-differences in antecedent mismatch than in match \([(3a)-(3b)]<[(3c)-(3d)]\). This effect started 251ms into presentation of \textit{que} ‘that’ and lasted for 265ms (Table 1). The first half of this effect had a central distribution across both hemispheres. The latter half exhibited a posterior distribution as per Figure 1.
A follow-up general linear model of average power over these clusters revealed a structure:antecedent interaction at the verb in the gamma rhythm, $F(1, 44) = 22.382, p = .0005$, which was not further qualified by group ($p = .290$). This was due to a significantly greater Mod-Comp power difference in the antecedent mismatch conditions [(3c) vs. (3d)], $t(45) = 4.031, p < .0005$, than in the antecedent match conditions [(3a) vs. (3b)], $t(45) = -2.071, p = .044$. In the antecedent mismatch conditions, the Mod structure was characterized by significantly greater average power. At the subordinator in the theta rhythm, there was a similar structure:antecedent interaction, $F(1, 44) = 4.155, p = .048$. This interaction was also not further qualified by group ($p = .862$). This interaction was again due to a greater Mod-Comp power difference in mismatch [(3c) vs. (3d)], $t(45) = 2.558, p = .014$, in the absence of any Mod-Comp power difference in the antecedent match condition [(3a) vs. (3b)], $p = .611$. These population-wide effects
in the gamma rhythm at the verb and in the theta rhythm at the subordinator suggest computations in which the complement structure completely relieves the cost of carrying an unresolved referential pronoun into the embedded clause.

**Table 1**

<table>
<thead>
<tr>
<th>Effect</th>
<th>Power</th>
<th>Hz</th>
<th>Word</th>
<th>Window</th>
<th>ClusterStat</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition evoked</td>
<td>34-40Hz</td>
<td>dit</td>
<td>394-498ms</td>
<td>-525.13</td>
<td>.007</td>
<td></td>
</tr>
<tr>
<td>Condition evoked</td>
<td>6Hz</td>
<td>que</td>
<td>251-516ms</td>
<td>-2117.2</td>
<td>.004</td>
<td></td>
</tr>
</tbody>
</table>

*Note.* A negative value in the ClusterStat column indicates greater Mod-Comp power differences in mismatch than in match.

**Table 2**

<table>
<thead>
<tr>
<th>Effect</th>
<th>Power</th>
<th>Hz</th>
<th>Word</th>
<th>Window</th>
<th>ClusterStat</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group evoked</td>
<td>18-20Hz</td>
<td>dit</td>
<td>314-364ms</td>
<td>-916.11</td>
<td>.008</td>
<td></td>
</tr>
<tr>
<td>Group evoked</td>
<td>5-6Hz</td>
<td>que</td>
<td>251-551ms</td>
<td>-1531.1</td>
<td>.024</td>
<td></td>
</tr>
<tr>
<td>Group induced</td>
<td>15-21Hz</td>
<td>que</td>
<td>362-521ms</td>
<td>1932.1</td>
<td>.002</td>
<td></td>
</tr>
</tbody>
</table>

*Note.* A negative value in the ClusterStat column indicates greater Mod-Comp power differences for NNSs than for NSs.

A main group effect arose in evoked power at 18-20Hz (beta rhythm) indicating greater Mod-Comp power differences across the antecedent match [(3a)-(3b)] and antecedent mismatch [(3c)-(3d)] distinction for NNSs than for NSs. It started 314ms into the presentation of *dit* and lasted for 150ms (Table 2). The first half of this effect had a left anterior distribution. The latter half was found along the anterior midline as Figure 2 shows. A second main group effect also showing greater Mod-Comp power differences for NNSs than for NSs arose at 5-6Hz (theta rhythm) in the evoked activity. It started 251ms into the presentation of *que* ‘that’ and lasted 300ms as shown in Table 2 and Figure 3.
verb *dit ‘said’ 18-20Hz (beta band)

Figure 2. ERP power group differences across all conditions at the bridge verb lasting 150ms.

subordinator *que ‘that’ 5-6Hz (theta band)

Figure 3. ERP power group differences across all conditions at the subordinator.

A main effect of group was found at *que ‘that’ in induced power from 15-21Hz (beta rhythm; Table 2) signaling greater power for differences in NSs than in NNSs as illustrated in Figure 4. It started 362ms into word presentation and it lasted for 159ms. It was broadly distributed in the right scalp.
subordinator *que* ‘that’ 15-21Hz (beta band)

![Brain activity image](Image)

362-521ms

[Mod-Comp in NS > Mod-Comp in NNSs]

**Figure 4.** Induced power group differences across all conditions at the subordinator.

### 4. Discussion

Population-wide Mod-Comp distinctions as a pronoun had not yet found a matching antecedent resulted in increased power for the Mod construction relative to the Comp construction. Hence, Mod-Comp structural representations were computed specifically at the bridge between clauses across the NS-NNS distinction as a presumed reflex of a dedicated network (RQ1). Turning to the nature of the network dynamics (RQ2), similar effects in the gamma and theta bands, crucially tied to the bridge verb and subordinator respectively, constitute prima facie evidence that predictions were computed on a short timescale at the verb and then were passed to processing, occurring over a longer timescale at the subordinator (Lewis et al., 2016). Group differences arose in the management of the processing network suggesting a distinct focus of the language network, as per CCT (RQ3). Analysis of evoked power at the subordinator revealed greater Mod-Comp differences in NNSs than in NSs in the theta band. This difference seems consistent with greater neuronal effort in the retention of representations over the embedded clause in NNSs. Relatedly, the analysis of evoked power at verb *dit* ‘said’ revealed greater sustained effort encoding the Mod-Comp distinction in NNSs than in NSs in the beta band. Analysis of induced activity in the beta rhythm at the subordinator showed that NSs produced greater power maintaining Mod-Comp differences than NNSs did. Given that the beta band is linked to the configuration of the language network, greater beta band power in induced activity in NSs at the bridge verb and in evoked activity in NNSs at the subordinator shows the allocation of neuronal effort to distinct tasks in NSs and NNSs. Given that the activity synchronized to stimuli likely arises as a “cell assembly is realized through a transient phase locking of EEG oscillations”
(Bastiaansen & Hagoort, 2003; p. 970), more power in evoked activity in the beta band at the verb in NNSs than in NSs suggests the recruitment of additional resources to sustain the capture of non-native input. The extra power in the theta band at the subordinator in NNSs in evoked activity also suggests additional effort in retaining the prediction for unification with upcoming linguistic material. Therefore, the event-related spectral perturbations appear to support a trade-off between input capture and commitment to structure.

5. Conclusion

Schwartz (1987, 1999) argued that second languages must arise within a representational and computational space reflecting a fixed neural architecture for language (Fodor, 1983, 2000), despite the presence of a native language encoded in the language network. Asymmetries consistent with highly domain-specific computations and representational distinctions in neuro-prediction at the bridge verb and in information unification at the subordinator indeed support a common neurocognitive prediction-unification processing reflex. This processing is modulated by additional effort directed at the capture of non-native input as revealed by greater evoked power encoding the Mod-Comp distinction in NNSs than in NSs in the beta and theta bands. Later-learned non-native representations presumably require this extra effort. Additionally, evoked vs. induced differences in the beta band seem consonant with the view that extra neuronal resources devoted to the capture of input in NNSs might diminish the network-level communication responsible for the construction of the incremental sentence-level interpretation. We propose CCT as a possible neurocognitive basis for the fragility of non-native parsing, with the beta band playing a crucial role.

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