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Comprehending Events on the Fly: Inhibition and Selection during Sentence Processing

Yanina Prystauka

Master's in Cognitive Science, University of Trento, 2015

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Comprehending Events of the Fly: Inhibition and Selection during Sentence Processing

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INTRODUCTION

Tracking objects as language unfolds

Imagine you are watching a cooking show. You can see the chef make lasagna and you can also hear her describe what she is doing. As you are hearing “now we are going to chop the onion”, you can actually see the chef locating the onion on her cutting board, taking the knife from the knife stand and chopping the onion. You can see the onion change from a round, ball-shaped object into a bunch of small white pieces. And despite the dissimilarity between the initial and the end state of the onion (before and after cutting), you still know that both the round object and the small white pieces can be referred to as onion and, moreover, they are the same instance of an onion (we will refer to such instances which are contextualized in space and time as tokens). In real life, after the onion has been chopped, there is no way back – it can’t become intact. In language, if you were to describe what the chef will do in the video to someone else, you would have more flexibility in which state of the onion to direct your listener’s attention to. You could say The chef will chop the onion. And then, she will smell the onion. in which case, upon hearing the onion in the second sentence your listener would most probably think of a chopped onion. However, you could also say The chef will chop the onion. But first, she will smell the onion. – in this case, the second sentence refers to the intact onion. The temporal connectives (And then vs But first) which differ between these two sentences point to which state of the onion (intact or chopped) to incorporate into the mental representation of the event described by the unfolding language which means that both should be available in the course of discourse comprehension. How these
representations interact during sentence-level language comprehension is, broadly, the question of the present study.

Some theories of language comprehension suggest that it relies on continuous mapping of lexical items onto the meaning representations stored in our semantic memory which eventually leads to the construction of situation models (Zwaan & Radvansky, 1998) – mental representations of situations described by language. When heard in isolation, individual words can elicit representations of generic objects stored in our long-term semantic memory and associated with a given word. For example, the word “onion” in isolation could elicit an aggregate mental image of a generic onion which lacks any spatio-temporal details. However, we usually communicate with longer utterances which create a context for the words they consist of, which leads to retrieval of more specific representations. The representations we build in our mind during language comprehension can be even more specific, for example in cases when language describes events that unfold in real time in front of our eyes. As in the first example, if we are watching a video of someone cooking we know very fine-grained details about the objects which are being referred to by language. If we hear the chef describing how she is going to cook the onion, we know the onion’s size (could be a small or an unusually large onion), color (could be red or yellow), location (changes as the language unfolds: first on the table, then on the cutting board, then on the frying pan), shape (perhaps not ideally round), etc. And even though the objects described by the language are out there in the real world, we are still building their mental representations which are dissociable from the perceptually available counterparts. A study by Altmann and Kamide (2009) used
eye-tracking and a visual world paradigm to explore the mapping between the language describing what happens to displayed objects and internal representations of those objects. Participants in the study saw static images depicting semi-realistic scenes and heard sentences describing people in the scene act upon objects in the scene either concurrently with scene presentation or following it. Critically, scenarios describing location change (e.g. *The woman will move the glass to the table*) were compared to scenarios which didn’t describe such change (e.g. *The woman is too lazy to move the glass to the table*). Altmann and Kamide found that after having heard the sentences describing location change, the participants were more likely to look at the new location when the target object (the glass) was referenced again later in the discourse (*She then poured some wine into the glass*) compared to the control sentences which didn’t describe location change. Thus, this study demonstrated that people update their internal representations of objects as dictated by language and such representations are separable from the perceptually salient visual representations of objects.

In the Altmann & Kamide (2009) study, the glass changed state insofar as it changed from one location to another. In the onion example above, the onion changes intrinsic state, and these distinct states are associated with the same object. For example, the sentence *The chef will chop the onion* introduces the onion and the details about it: it’s the onion in the kitchen (and not in the garden or on the shelf in a store) and it is about to undergo change (it will be chopped). The event of chopping entails changes in the state of the onion and a single representation of an onion is not enough to understand that the event took place, i.e. *chopping* inherently implies the transition of an onion from an intact
to a chopped state. All these details about the onion, including featurally contrasting representations of its initial and end states, now become a part of this particular onion’s history. The unfolding language may selectively refer to either state of the onion, i.e. *And then/but first, she will smell the onion*. How much of this onion’s history is retrieved at its second mention? One possibility is that both representations of the onion are active at this point, with each competing for selection – a competition which needs to be resolved whenever the same object is referred to again. In this case, no matter what the temporal term is in the subsequent sentence (*And then or But first*), the processing cost would be higher than in scenarios which didn’t introduce the object in different states. Another possibility is that we keep in our episodic memory only the most recent representation, i.e. the chopped onion, in which case we would predict the increase of processing cost only in the sentences which make one travel in time and retrieve the initial state as in *But first, she will smell the onion*. Finally, the reference to the onion could in principle elicit the prototypical representation of the onion (presumably, in its intact round shape), in which case in sentences which refer to the resultant changed state (*And then sentences*), the prototypical representation needs to be adjusted, which could also lead to increased processing cost. To summarize, the first possibility predicts interference and competition (and as a consequence, increase in processing cost associated with resolving it) between state representations regardless of the intended state. The second possibility predicts interference between the most recent state and the initial state only for the *But first* scenarios, while the third possibility predicts interference between the prototypical object and its changed state only for the *And then* scenarios.
One way to explore these possibilities is to look into the brain and see whether brain areas associated with competition during selection of alternative incompatible interpretations would also be recruited for processing the object which underwent change, and if so, in which scenarios (And then, But first or both?). One such brain area of interest is left posterior ventrolateral prefrontal cortex (left pVLPFC) (for a discussion, see Thompson-Schill, Bedny, & Goldberg 2005). Hindy, Altmann, Kalenik, & Thompson-Schill (2012) ran an fMRI study to look at whether left pVLPFC would be sensitive to the state change manipulation, and if so, under which conditions. They found that indeed left pVLPFC was more active as participants read sentences describing significant change as compared to scenarios which entailed minimal or no change. Moreover, activation in left pVLPFC correlated with the degree of change (rated in a separate on-line norming study) suggesting that the more dissimilar the representations are, the more they interfere. This interference took place regardless of whether the subsequent sentence referred to the resultant (And then, …) or the initial (But first, …) states of the object, suggesting that both are available and competing for selection given their mutual exclusivity.

To further explore this object states competition effect and whether state representations interfere only when they are bound to the same object token (and, as a consequence, are mutually exclusive), Solomon, Hindy, Altmann, & Thompson-Schill (2015) ran a study in which they had an additional manipulation of token reference (as well as the original state change manipulation), i.e. half of their sentence pairs introduced a new token in the second sentence (And then, she will smell another onion). The results
showed that activation in left pVLPFC increased in response to substantial change condition only when the second sentence referred back to the same object token and not when it introduced a new object token. This result was interpreted as showing that only representations that are mutually exclusive (such as different state representations of the same object token) interfere with each other and compete for selection, while state representations of distinct tokens don’t interfere. This finding is in line with the idea (coming from studies of visual attention) that our cognitive system has a mechanism of individuating and keeping track of object tokens independent of their visual properties, i.e. two identical objects with the same perceptual properties can still be recognized and maintained as two separate entities (Pylyshyn, 2001). Under the account of visual indexing developed by Pylyshyn (2001), an individual token gets assigned a visual index which makes it possible to keep track of this token over time and represent it as a single entity despite changes in its location and visual properties. However, this line of research doesn’t address the nature of representational content which is being tracked and neural mechanisms by which such representations are built and maintained.

To summarize, experiments by Hindy et al (2012) and Solomon et al (2015) suggest that our comprehension system keeps track of different instantiations of an object which interfere with each other upon the object’s subsequent mentions and these representations don’t interfere with the representations of newly introduced objects of the same type. Localization of this effect, in pVLPFC which is known to be sensitive to conflict resolution, suggests that the processing cost might be due to competition between several incompatible representations of the same object. However, such competition is
perhaps not a unitary process and may rely on multiple sub-processes such as selective attention, suppression, updating of the current cognitive state, etc that get carried out in response to the trigger stimulus, in our case, the token which has undergone change. Due to the poor temporal resolution of fMRI, it is impossible to establish the dynamics of these processes and where in the sentence they occur. Moreover, as these processes unfold, they do so dynamically, meaning that at whichever point in the sentence we might begin to see their unfolding, they may unfold not just across time (waxing and waning in intensity, perhaps) but also across electrode space. EEG, unlike fMRI, provides greater temporal resolution and could in principle allow us to inspect the dynamics of representation retrieval under the magnifying glass.

**EEG for studying cognition**

EEG is a popular methodology in psycholinguistic research. Traditionally, psycholinguistics has focused on event-related potentials (ERPs), which are computed by averaging time-locked segments of the EEG signal across multiple trials. ERP is a measure of purely evoked activity and a lot of information is lost during the averaging across multiple trials. An alternative to ERP are time-frequency representations (measures of intensity of different frequency components in the EEG signal), and these could be a more sensitive measure because (i) they preserve induced activity which might be different between our substantial and minimal change scenarios, (ii) this measure includes the additional dimension of frequency and (iii) there is a rich literature relating fluctuations of power at different frequencies over time to domain-general cognitive processes such as memory encoding and retrieval, inhibition, attention, maintenance of
representations and their integration into the current context, etc. all of which could be implicated in the process of retrieving representations of objects that have been in multiple states.

Traditionally, frequencies in the EEG signal are organized into 5 bands: delta (1-3 Hz), theta (4-7 Hz), alpha (8-12 Hz), beta (13-30 Hz), gamma (>30 Hz). Neural activity at all these bands has been implicated in different cognitive processes across varying paradigms and modalities, as well as having been found to be sensitive to syntactic and semantic manipulations in sentence-level comprehension tasks. Below, we provide an outline of functional processes associated with each frequency band with a specific focus on brain oscillatory dynamics during sentence-processing. As we review theories of brain oscillations and cognition, we discuss whether these theories could account for one or more aspects of our findings on interfering object-states.

**Neural oscillations and cognition**

The time-frequency analysis of neural activity allows us to look at brain oscillations over time. Increases in power at certain frequencies indicate synchronization of the neural activity at that frequency, decreases in power indicate desynchronization. Terms such as de/synchronization can be used to describe either long-range coordination between different nodes of the same functional network or synchrony of neurons at a local level (for discussion, see Bastiaansen & Hagoort, 2006). To examine the former, a coherence analysis is necessary. Here we use time-frequency analysis to examine the latter, i.e. local synchrony which occurs when large populations of neurons synchronize their activity, and this signal becomes strong enough to propagate through the brain tissue.
and skull and reach the electrodes. Whether the results of this analysis indicate that a known physiological mechanism that produces the oscillation in the brain (such as hippocampal theta rhythm, for example) is at play is a difficult question and perhaps only in-vivo recordings of brain electrical activity can give a direct answer to it (for discussion, see Cohen, 2014, pp.270-272). However, using indirect techniques such as M/EEG across multiple paradigms and modalities to study the healthy human brain may bring us closer to understanding the functional role of brain electrical dynamics at different frequencies. The hope is that combining this knowledge with the evidence obtained using in vivo techniques will ultimately help us discover the neurophysiological mechanisms underlying brain function.

On the one hand, the EEG literature investigating the neural correlates of brain function using the time-frequency analysis is huge. On the other hand, the phenomenon we are particularly interested in – the dynamic building, maintaining and retrieving of object-states representations – is part of a novel theory of event representation, itself based on a novel phenomenon (Hindy et al., 2012, are the first to report it) and it would be no exaggeration to say that until now there have been no EEG experiments which have directly tested the predictions of this theory. Thus, we treat this study as exploratory. However, we can draw some broad predictions from the literature on oscillations and language comprehension broadly and sentence processing specifically (since in the present study events were described by language), memory encoding and retrieval (since discourse comprehension requires constant retrieving of representations from semantic memory and their grounding in the episodic context of the discourse) as well as inhibition
and attention (since we believe that these processes could be differentially manipulated by our state change and reference manipulations).

**Beta and Gamma Oscillations**

Using time-frequency analysis for studying the neural correlates of different aspects of language comprehension doesn’t have a very long history; however, this approach is gaining pace. Studies on sentence processing have mostly employed syntactic violations (of gender and number agreement, word category, phrase structure, verb tense) and semantic anomalies. There is an emerging pattern of results such that syntactic violations elicit a decrease in beta power compared to correct sentences (Bastiaansen, Magyari, & Hagoort, 2010; Davidson & Indefrey, 2007; Lewis, Lemhöfer, Schoffelen, & Schriefers, 2016; Kielar, Meltzer, Moreno, Alain, & Bialystok, 2014; Kielar, Panamsky, Links, & Meltzer, 2015) while semantic anomalies lead to decrease in gamma (Bastiaansen et al, 2010; Bastiaansen and Hagoort, 2015; Vignali, Himmelstoss, Hawelka, Richlan, & Hutzler, 2016; Penolazzi, Angrilli, & Job, 2009; Rommers, Dijkstra, & Bastiaansen, 2013; Wang, Zhu, & Bastiaansen, 2012). Even though the experimental stimuli in the present study don’t contain any violations, the predictive coding framework developed by Lewis and Bastiaansen (2015) accounts for the above described findings and generalizes the mechanisms involved for processing violations to sentence-level meaning comprehension which makes these beta and gamma effects more relevant for our question of interest. Lewis and Bastiaansen emphasize the hierarchical aspect of information processing during language comprehension: higher-level representations of meaning or structure are built as lower-level units are processed. Anticipation is an
essential component of this workflow because in constraining contexts higher-level representations are pre-activated ahead of the incoming lower-level information and top-down predictions are being propagated down the processing stream. According to the predictive coding framework, a violation or anomaly serves as a cue to the language comprehension system that the meaning or structure representation built so far is problematic in some way and must be reconsidered. The framework accounts for the beta effects described above by suggesting that beta activity is associated with the maintenance of such sentence-level meaning representation under construction and propagation of top-down predictions: beta power increases as the sentence unfolds and decreases upon encountering a violation. Lower and middle gamma frequency (≈30-60 Hz) reflects matching between top-down predictions and incoming linguistic input: gamma is higher when the pre-activated representation matches the bottom-up input which is the case of sentences which end with a very high cloze probability word, as demonstrated by Wang et al, 2012. Higher gamma (>60 Hz) might be involved for lateral inhibition of competing representations (for experimental evidence, see Nieuwland & Martin, 2017).

So what is the link between the above discussed findings and predictive coding framework on the one hand and our object-state change manipulation on the other? We believe that when the discourse describes an event that results in change of the object state, representations of the object in its different states are being maintained throughout discourse comprehension. Comparing scenarios which describe change (chop the onion) to those which don’t (smell the onion) means that we are comparing two qualitatively (and possibly quantitatively) different meaning representations, with that of the changed object
being “richer” and having more details (because the end state of the object which underwent substantial change differs from its initial state on one or more featural dimensions and, under our account, both such feature sets are retained). Thus, beta frequency which, according to Lewis and Bastiaansen, reflects maintenance of the sentence-level meaning representation, might distinguish between two such sets of representations, especially in scenarios which require our comprehension system to switch from the current token to instantiate a new one (as in And then, she will weigh another onion): switching from the intact onion to a new instance of an onion (presumably, also intact) might be less problematic than switching from a “richer” representation. Under the predictive coding account, we could also expect effects in low and middle gamma because there might be differences in how likely the event in the second sentence to follow substantial and minimal change events described in the first sentence.

High gamma could in principle also be relevant for the present study. Nieuwland and Martin (2017) have reported the results of time-frequency analysis of 4 EEG studies which all investigated oscillatory correlates of anaphoric reference. Results of these 4 studies which varied in modality (auditory/visual), language (Dutch, Spanish, English) and type of referential expression (noun phrase/pronoun) showed increased gamma activity for referentially coherent expressions compared with expressions that had either more than one or no antecedents. The case of referential ambiguity where there is more than one antecedent for the referential expression is similar to our case of multiple object states where there is more than one state for the object which underwent change. Our minimal change condition is similar to the case of referentially coherent expressions from
Nieuwland and Martin, thus we might expect higher gamma in the minimal change (referentially coherent) condition compared to the substantial change (referentially problematic) condition. There is however a difference between the referential ambiguity and state change cases: in the former, ambiguity is between different tokens, in the latter is it between different states of the same token. Results of fMRI studies on referential ambiguity and object-states competition effect don’t converge. As has been discussed above, comprehending events which entail change leads to increased activation in LIFG – an effect interpreted as indicating conflict between multiple competing representations (Hindy et al, 2012; Solomon et al, 2015). Referential ambiguity did not elicit increases in LIFG activation, but instead lead to increased activation in medial and bilateral parietal, medial frontal and right superior frontal regions (Nieuwland et al, 2007) – brain areas associated with problem-solving. The authors interpreted this effect as indicating that selecting the correct antecedent relies not on resolving competition between several potential referents, but instead on inference- and decision making for solving the problem. If EEG and time-frequency analysis are sensitive to the same processes as fMRI, then we shouldn’t expect the results of the present analysis to converge with those of Nieuwland and Martin. However, it could be the case that gamma is sensitive to neither problem solving nor conflict resolution, but instead to some cognitive processes shared between processing referential ambiguity and comprehending change in which case we might expect gamma effect.
**Theta Oscillations**

Theta frequency has also been implicated in sentence processing and is responsive to semantic manipulations, such as semantic anomalies (Davidson & Indefrey, 2007; Bastiaansen and Hagoort, 2015; Hald, Bastiaansen, & Hagoort, 2006; Wang et al, 2012), open vs close-class words comparison (Bastiaansen et al., 2005), comparison of words with visual vs auditory semantic properties (Bastiaansen, Oostenveld, Jensen, & Hagoort, 2008), which suggests that theta activity might be associated with lexical-semantic retrieval. Theta frequency has also been extensively studied outside the sentence processing domain by memory researchers. For example, theta has been implicated in episodic memory encoding and retrieval: theta differentiates between items which will be later remembered during the encoding phase and between old and new items during the retrieval phase (Klimesch, Doppelmayr, Schimke, & Ripper, 1997; Klimesch, Doppelmayr, Russegger, & Pachinger, 1996; Burgess & Gruzelier, 1997) and increases with increased memory load (Jensen & Tesche, 2002), for a review, see Klimesch, Schack, & Sauseng, 2005. In our paradigm, maintaining multiple or more complex representations of an object in its different states might lead to higher memory load and potentially induce increase in theta at retrieval in the state change condition compared to the minimal change condition.

**Alpha Oscillations**

Finally, alpha is perhaps the most extensively studied frequency in the human EEG. A well-known oscillatory signature of information processing is alpha suppression. Since its discovery by Hans Berger in the late 1920s, it has been replicated many times.
The basic finding is that alpha desynchronizes when the eyes are open compared to when the eyes are closed. In language-related tasks, alpha desynchronization has been found in response to semantic judgement tasks (Röhm, Klimesch, Haider, & Doppelmayr, 2001; Klimesch, Doppelmayr, Pachinger, & Russegger, 1997) and syntactic violations (Bastiaansen et al, 2010; Davidson & Indefrey, 2007; Kielar et al, 2014; Kielar et al, 2015). But the general finding is that alpha desynchronizes for active information processing.

Somewhat paradoxically, in memory tasks involving retention of items, alpha power increases proportionally to the number of items which need to be maintained in memory (Jensen, Gelfand, Kounios, & Lisman, 2002; Tuladhar et al, 2007; Klimesch, Doppelmayr, Schwaiger, Auinger, & Winkler, 1999). The gating by inhibition hypothesis (Jensen & Mazaheri, 2010) as well as the inhibition-timing hypothesis (Klimesch, Sauseng, & Hanslmayr, 2007) account for this paradox taking into account the timing and topography of alpha effects. According to these two very similar theories, alpha increase indicates inhibition of task-irrelevant brain areas or functional networks which facilitates information processing in relevant areas/networks. If EEG will be sensitive to the effect found with fMRI (object-states competition effect), we might expect effects in the alpha frequency (because resolving competition requires inhibition of the irrelevant object-state).

There are also delta oscillations which are generated in sleep, but are also modulated by the reward system and saliency of the target (Knyazev, 2007), but it is difficult to relate these to the present study, and thus we are neither reviewing nor including delta in the actual analysis.
The present study

In the present study, we want to investigate how representations of objects in their different states are built, maintained and retrieved as language unfolds, as well as how our comprehension system switches from processing one token to instantiating a representation of a different token of the same type. We manipulated the amount of change an object undergoes (and, as a consequence, complexity of history associated with the object), as well as the referent of the unfolding discourse (whether the same or another token is being referred back to): The chef will weigh/chop the onion. And then, she will smell the/another onion. We measured participants’ EEG while they read pairs of sentences. Given that EEG power fluctuations in theta, alpha, beta and gamma frequencies have been implicated in processes which could also be employed for tracking objects through unfolding language, we expected oscillations at one or more of these frequency bands to be sensitive to our manipulations.
METHODS

Participants

Thirty-seven participants were recruited from the student population at the University of Connecticut in accordance to the IRB approval. They received course credit for their participation. Six participants were eliminated due to technical problems (equipment and script failure). The remaining 31 participants (19 females; age range = 18-22 years) were native speakers of English, right-handed, had normal or corrected to normal vision and hearing, and no history of neurological disorders. Data from several more participants had to be discarded after preprocessing due to excessive EEG artifact (details are provided below).

Materials and design

Each participant completed 320 trials. Experimental stimuli (N=160) were designed to elicit the intersecting object-states effect and appeared in 4 conditions (40 sentences per condition) in a 2 by 2 design (see Table 1 for the summary of conditions). All experimental items consisted of two parts. In the first sentence, we manipulated the degree of change the object underwent as a result of someone or something acting upon it, e.g. The chef will weigh the onion (minimal change) or The chef will chop the onion (substantial change). State change ratings were collected in a separate on-line norming study (described below). The verbs were matched in length and frequency\(^1\). In the second sentence, we manipulated the token reference, i.e. the sentence either referred back to

\(^1\) All frequency values were obtained using the SUBTL Word Frequency database (Brysbaert and New, 2009).
the previously introduced token (And then, she will smell the onion) or introduced a new token of the same type (And then, she will smell another onion).

Filler sentences (N=160) were designed to potentially (i) elicit transient lexical and referential ambiguity effects and (ii) reduce predictability of the object in the second sentence. Lexical and referential ambiguity are of interest to us since they also arise in cases when there is more than one representation bound to the lexical item, just like in the case of objects which have undergone a significant change of state (and any further reference to such objects could lead to transient ambiguity between different states). It could be that processing the object which has been in two distinct states relies on the same mechanisms as resolving lexical and/or referential ambiguity which would be reflected in similar EEG patterns for all these types of ambiguity. However, there is one major difference between lexical and referential ambiguity on the one hand and states ambiguity on the other, with the latter being between two representations of the same instance of an object token and the former – between representations of different objects. Taking into account this difference as well as the fact that in our filler sentences the critical entity is mentioned only once (and not later referred back to), processing a lexically or referentially ambiguous entity would require an inference about which referent is more likely given the context, whereas processing the critical entity from the main experimental conditions would require retrieving that item’s history. Processing these different types of ambiguities could rely on different mechanisms and engage different brain areas, and thus result in different EEG patterns.
As mentioned above, filler sentences also served the purpose of reducing predictability of the object in the second sentence. Eighty filler sentences had the same structure as experimental stimuli, however they introduced a new object type in the second part (e.g. *The woman will wash the floor. And then, she will unroll the carpet*). Half of these stimuli (N=40) had a lexically ambiguous item in the second sentence (e.g. *The woman will wash the floor. And then, she will unroll the runner*). We manipulated the context in order to bias the ambiguous items towards the less dominant meaning and thus create transient competition between the dominant meaning and the contextually biased subordinate meaning (meaning dominance was based on the norming studies by Elston-Guettler & Friederici, 2004; Gorfein, Viviani, & Leddo, 1982; Nelson, McEvoy, Walling, & Wheeler, 1980; Titone, 1998). The sentences were designed this way in order to make them elicit *transient* uncertainty rather than unresolved ambiguity because the former is more similar to a conflict elicited by multiple states of an object. Nouns in the second sentence were matched on length and frequency.

Finally, we also included 80 filler sentences with two clauses within a single sentence. Half of them (N=40) were designed to elicit referential ambiguity, such as *John valued Edward because he was very knowledgeable*, where *he* can refer to both John and Edward. We used the implicit causality database provided by Ferstl et al (2010) to choose the verbs which had a 70% bias either towards NP1 (N=20) or NP2 (N=20) to make sure that the ambiguity is resolved. Again, such transient ambiguity is more similar to the ambiguity arising from the competing objects states which is also transient and resolved in favor of the state relevant in the context of the sentence. The rest of these
filler sentences (N=40) were designed in such a way that the pronoun selectively pointed to either actor or patient of the sentence (e.g. *Daphne valued Edward because he was very knowledgeable*).

We didn’t run additional norming for the lexical and referential ambiguity sentences; the results of the analyses performed on these sentences should therefore be interpreted with caution.

<table>
<thead>
<tr>
<th>Condition Code</th>
<th>Condition</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Minimal Change, Same Object Token</td>
<td>The chef will smell the onion. And then, she will weigh the onion.</td>
</tr>
<tr>
<td>2</td>
<td>Substantial Change, Same Object Token</td>
<td>The chef will chop the onion. And then, she will weigh the onion.</td>
</tr>
<tr>
<td>3</td>
<td>Minimal Change, Another Object Token</td>
<td>The chef will smell the onion. And then, she will weigh another onion.</td>
</tr>
<tr>
<td>4</td>
<td>Substantial Change, Another Object Token</td>
<td>The chef will chop the onion. And then, she will weigh another onion.</td>
</tr>
<tr>
<td>5</td>
<td>Lexically Ambiguous</td>
<td>The woman will wash the floor. And then, she will unroll the runner.</td>
</tr>
<tr>
<td>6</td>
<td>Lexically Unambiguous (control for 5)</td>
<td>The woman will wash the floor. And then, she will unroll the carpet.</td>
</tr>
<tr>
<td>7</td>
<td>Referentially Ambiguous</td>
<td>John valued Edward because he was very knowledgeable.</td>
</tr>
<tr>
<td>8</td>
<td>Referentially Unambiguous (control for 7)</td>
<td>Daphne valued Edward because he was very knowledgeable.</td>
</tr>
</tbody>
</table>

Table 1. Examples of the experimental and filler sentences for each condition.

To summarize, each subject was presented with 320 trials, split across 8 conditions (4 critical, 4 filler), with 40 items in each condition. All sentences were counterbalanced across four experimental lists using a Latin square design and pseudo-randomized so that there were no more than three consecutive trials from the same condition.
**Change ratings**

Change ratings for the actions described in the first sentence of each experimental sentence pair were collected on-line using Qualtrics software. There were 160 sentence pairs, yielding a total of 320 first sentences, evenly split between substantial and minimal change conditions, resulting in 160 sentences per condition which were further split across 4 stimuli lists, so that each participant saw only one version of each sentence (i.e. describing either substantial or minimal change). Participants (N=159) were asked to rate how much the object changes as a result of the action described on a scale from 1 (no change) to 7 (big change). Sentences in the minimal change condition received an average rating of 2.17 (sd = 0.86), sentences in the substantial change condition received an average rating of 4.31 (sd = 0.97). Thus, there was a significant difference between the average change ratings for the substantial and minimal change conditions (t = -19.9, df=159, p<0.001). A post-hoc item analysis showed that there were 4 sentences with reverse change ratings. They were removed from the analysis (thus instead of 160 experimental trials per person, there were 156 trials). The distribution of responses is illustrated in Figure 1.
Sentence pairs in the substantial and minimal change conditions differed only by the verb (and, as a consequence, event) in the first sentences, while the second sentence was kept constant across conditions. To see whether the event described in the second sentences was equally likely to follow substantial or minimal change events, we collected ratings (using Qualtrics software) for the likelihood that the second sentence of each sentence pair would follow the first sentence. Items were split into 4 lists with an equal amount of (randomized) substantial and minimal change items in each condition. Participants (N=26) were asked to rate *How likely is it that the event described in the second sentence would follow the event described in the first sentence?* on a scale from 1 (*very unlikely*) to 7 (*very likely*). For the same token reference, sentence pairs in the minimal change condition received an average plausibility rating of 5.19 (sd = 0.93), sentence pairs in the substantial change condition received an average plausibility rating...
of 4.93 (sd = 1.02). For another token reference, sentence pairs in the minimal change condition received an average plausibility rating of 3.51 (sd = 0.77), sentence pairs in the substantial change condition received an average plausibility rating of 3.63 (sd = 0.87). Thus, events involving substantial change were rated as less likely to be followed by events described in the second sentence than events involving minimal change (p=0.0004 for the same and p=0.03 for another token reference). We return to this issue in the Results and Discussion sections.

Procedure

Before the experiment, participants were asked to read and sign a consent form and fill out the demographic information forms. Together with the subject preparation (see EEG Data Acquisition section) this part took approximately 30 minutes.

The experiment took place in a sound-attenuated chamber. Participants were asked to read sentences and answer comprehension questions, while trying to minimize movements and blinks during sentence presentation. The experiment started with 10 practice trials, followed by 320 experimental and filler items, split into 8 blocks. Sentences were presented on a Dell monitor using PsychoPy software (Pierce, 2007). Subjects were seated 80 cm away from the screen. Each trial started with a black fixation box presented for 1300 msec on a grey background, in the center of the screen. Sentences were then presented one word at a time with words presented in a yellow font inside the fixation box at a fixed rate. Each word was presented for 300 msec, followed by an interstimulus interval (ISI) of 300 msec. After the last word of the sentence disappeared from the screen, the blank fixation box remained on the screen for 1000 msec. 12% of trials were
followed by yes/no comprehension questions (N=39). Participants were instructed to press the “f” and “j” keys on a keyboard to give their responses and to use the “j” key to proceed to another sentence whenever they felt ready. After every block, they were given feedback about their progress (i.e. how many sentences were read, how many were left, how many comprehension questions were answered correctly). Accuracy for the comprehension questions was used as an indication that participants read the sentences carefully. On average, performance accuracy was 94%. The time on task was approximately 1 hour 20 minutes.

**EEG data acquisition**

EEG was recorded using a 256-channel HydroCel Geodesic Sensor Net at a sampling rate of 1000 Hz. The data were amplified using a Net Amps 400 Amplifier (Electrical Geodesics, Inc., Eugene, OR). Recordings were referenced on-line to Cz and re-referenced off-line to the average of all channels. There were no on-line filters. Impedances were set below 50 kΩ.

**Data preprocessing**

Preprocessing and analyses were performed using the Fieldtrip toolbox for Matlab (Oostenveld, Fries, Maris, & Schoffelen, 2011). A high-pass filter at 0.1 Hz and a low-pass filter at 55 Hz were applied to the continuous data. Then, epochs ranging from 1750 msec before and 2200 msec after the critical word (see below) onset were extracted with a 30 msec offset (because additional testing showed that our stimuli appeared on the screen with a ~30 msec delay). Even though the final analysis was performed on shorter epochs, preprocessing was done on longer time-windows to provide sufficient data.
padding for the subsequent time-frequency analysis. In the experimental conditions, preprocessing was time-locked to the noun phrase in the second sentence, e.g. *And then, she will weigh the/another onion* (however, noun phrases were later split into separate determiner and noun trials for the final analysis, see below for more details). In the lexical ambiguity condition, the critical word was the last noun in the second sentence, e.g. *And then, unroll the carpet/runner*. In the referential ambiguity condition, the critical word was the pronoun, e.g. *John valued Edward because he was very knowledgeable*.

To maximize reproducibility, we tried to use automatic approaches for data preprocessing whenever it was possible. After segmentation, the data were demeaned and resampled at 500 Hz. Next, bad channels were automatically identified (channels were classified as contaminated if their variance exceeded a z threshold of 1). Such channels were removed from the data and interpolated using spline interpolation. The average number of removed channels per person was 9.7 (~4%), however it varied substantially among individuals (sd = 7.7). Next, a principal components analysis reduced the dimensionality of our data to 60 components, on which an independent components analysis was performed. Blinks, eye-movements and the remaining line noise components were identified manually (this was the only subjective step in the entire routine) and removed from the data. On average, 3.1 components were removed per participant (sd = 1.4). Finally, the data were re-referenced to the average of all channels (and Cz channel was recovered through this procedure, which resulted in a total of 257 channels). Ideally, reference sites shouldn't pick up brain activity. In reality, this is not the case and even electrodes at the mastoids or earlobes (which often serve as a reference)
can pick up activity from the temporal lobe or muscle-related artifacts (for more details, see the discussion of the no-Switzerland principle by Luck (2014), pp.151-165). Moreover, in high-density systems such as ours if we were to choose mastoid channels as a reference, some recording sites would be too close to the reference channels and activity recorded at such sites would be similar to those of the reference channels. On the other hand, given that “the integral of negative and positive potential fields in a conducting sphere sums to exactly zero” (Dien, 1998, p. 35), we used average reference to take advantage of the fact that 256 channels allow for decent sampling of the head surface potential and thus could be used as an approximation of a true zero.

The remaining preprocessing steps (i.e. de-trending and threshold-based artifact rejection) were performed for experimental and filler items separately (because length of the segments of interest varied for experimental and filler trials). Below are the details of the remaining preprocessing steps and analysis parameters for the experimental trials. Further information about the preprocessing and analysis of the filler items, as well as the discussion of results is provided in Appendix C.

**Choice of the critical word and baseline period**

One aim of the present study was to investigate the dynamics of the interaction between multiple representations of the same object. Our region of interest, therefore, is the end of the second sentence of each sentence pair, where the object which was introduced in the first sentence is referred back to again. However, since (i) we used RSVP paradigm and presented strictly one word at a time (so a determiner and a noun were presented separately) and (ii) given the fact that the noun from the first sentence
was repeated in the second sentence on most trials\(^2\) (e.g. *The chef will smell the onion. And then, she will weigh the onion.*), we assumed that participants would anticipate the ending of the sentence and any potential effects could emerge even before presentation of the final noun, i.e. at the determiner (c.f. the anticipatory processes observed by Altmann & Kamide, 1999; DeLong, Urbach, & Kutas, 2005). For this reason, we split each trial, time-locked to the determiner and lasting until the offset of the final noun, into separate determiner and noun epochs for further preprocessing and analysis.

Since we are interested in the effect of retrieval of a target representation (and potential conflict due to multiple competing representations of the object in its different states), we chose the verb before the final noun as our baseline. This ensures that any differential activation in response to the critical words (i.e. determiner and noun) in the substantial and minimal change conditions is due to the retrieval and not maintenance of object’s multiple states.

**Trials time-locked to the determiner**

We redefined experimental trials to include 850 msec before and 860 msec after the determiner onset which would allow us to look at the power spectrum associated with the determiner in the time-window of 600 msec before and 600 msec after the determiner (given the parameters of the time-frequency analysis, see below). After removing the linear trend from the trials and running automatic artifact rejection, we eliminated

\(^2\) 25\% of trials – these were filler items designed to elicit referential ambiguity and their controls – consisted of one sentence and all had the same sentential pattern, e.g. `<John valued Edward> because s/he `<was very knowledgeable>`, where the agent and the patient were always proper names. 75\% of trials had the following structure: The `<agent>` will `<perform an action on the object>`. And then, s/he will `<perform another action on the/another object>` of which two thirds had a repeating noun. If we believe that participants were sensitive to this distribution of items (for example, a proper name could serve as a cue that the trial will consist of one sentence) and anticipated repetition of the noun on only two-sentence trials, then we could expect participants to have an even stronger expectation that the noun will be repeated (since it was true for ~66\% of two-sentence pairs) which could lead to early effects at the determiner.
participants (N=8) who had more than 50% of trials with activity exceeding the +/-100 mV threshold. Approximately 16% of trials were removed from the data of the 23 participants who entered the final analysis. The remaining trials were equally distributed among conditions (Minimal Change, Same Object Reference = 33, Substantial Change, Same Object Reference = 33, Minimal Change, Another Object Reference = 33, Minimal Change, Another Object Reference = 33).

**Trials time-locked to the noun**

To compute power on the noun relative to the verb, we extracted 850 msec before the determiner (verb-associated activity) and concatenated these epochs with the 860 msec following the noun onset. We further ran de-trending and automatic artifact rejection (using the +/-100 mV threshold) on such concatenated trials. 8 participants who had less than 50% of remaining trials were eliminated. Approximately 19% of trials were removed from the data of the 23 participants who entered the final analysis. The remaining trials were equally distributed among conditions (Minimal Change, Same Object Reference = 31, Substantial Change, Same Object Reference = 31, Minimal Change, Another Object Reference = 31, Minimal Change, Another Object Reference = 32).

**Time-frequency analysis**

To calculate power spectrum in the 4-30 Hz frequency range, a 500 msec long time-window and a Hanning taper were used. Power changes were computed in steps of 10 msec and 2 Hz. To calculate power spectrum in the 30-55 Hz frequency range, a 200 msec long time-window and a Hanning taper were used. Power changes were computed in steps of 10 msec and 5 Hz. Then, time-frequency representations were averaged for
each subject, separately for each of the four experimental conditions. Post critical-word subject averages were expressed as a relative change from the baseline interval of 600 to 250 msec before the critical word (which corresponds to verb presentation and 50 msec of blank screen following it). A cluster-based random permutation test was used to compare the contrasts of interest.

**Statistical analysis**

A cluster-based random permutation approach (Maris & Oostenveld, 2007) was used to compare the neural response between conditions. Since this approach only allows for pairwise comparisons, the following contrasts were considered and are reported (separately for the determiner and noun trials):

- Same object token
  - Minimal Change vs Substantial Change
- Another object token
  - Minimal Change vs Substantial Change

Data points in the 0 to 600 msec time-windows relative to the critical word (determiner and noun) onset were entered into the final analysis. For all conditions, data from all 257 EEG channels were included in the analysis. Separate analyses were performed for each of the four frequency bands: theta (4-7 Hz), alpha (8-12 Hz), beta (13-30 Hz) and gamma (30-55 Hz). For every time-frequency-channel data point a dependent samples two-tailed t-test was performed to compare activation between conditions. All data points which met a significance level of \( p=0.025 \) per tail were clustered based on temporal adjacency, and a cluster-level statistic was calculated by adding together all t-values within a cluster. Next, the condition labels were swapped and a t-test was run for such permuted samples. This procedure was repeated 1000 times and a histogram was
created based on the resulting t-values. If the cluster-level statistic fell within highest or lowest 2.5th percentile of the permutation histogram, the effect was said to be significant.

RESULTS

See Table 2 for the summary of results for the determiner and noun trials. See Appendix C for the summary of results for the filler trials.

Power changes time-locked to the determiner

For the same token reference, the cluster-based random permutation test revealed a significant difference (p=0.01) between the substantial and minimal change conditions in one of the three tested frequency bands, namely in alpha3 (8-12 Hz): there was more alpha power in the substantial change condition relative to the minimal change condition. The difference was most pronounced between 80 and 510 msec after the determiner onset and had a left temporal distribution (see Figure 2). Testing in the theta (4-7 Hz), beta (13-30 Hz) and gamma (30-55 Hz) frequency bands didn’t yield significant results.

For another token reference, the cluster-based random permutation test didn’t reveal significant differences between the substantial and minimal change conditions in any of the frequency bands. However, testing in the beta frequency band (13-30 Hz) revealed a marginally significant difference (p=0.07). In Figure 3 which visualizes the results for another token reference, we chose to plot topographies averaged across the same time (80-510 msec) and frequency (8-12 Hz) windows in which the difference persisted.

3 To make sure that this alpha effect is not due to the differences in plausibility of the second sentence following the first sentence between the substantial and minimal change conditions (for more details, see Methods section), we removed 19 items with the largest differences in plausibility ratings between the conditions so that the average difference wasn’t significant anymore, recomputed time-frequency representations and re-ran statistics on this new reduced dataset. The alpha effect persisted.
between the two change conditions (substantial and minimal) was significant for the same token reference to allow for comparison of alpha dynamics between the two reference conditions (same and another).

<table>
<thead>
<tr>
<th>Determiner</th>
<th>0-600 msec</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>SubSame-MinSame</td>
</tr>
<tr>
<td>theta (4-7Hz)</td>
<td>0.8 (neg)</td>
</tr>
<tr>
<td>alpha (8-12Hz)</td>
<td>0.01 (pos)</td>
</tr>
<tr>
<td>beta (13-30Hz)</td>
<td>0.39 (pos)</td>
</tr>
<tr>
<td>gamma (30-55Hz)</td>
<td>1 (neg and pos)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Noun</th>
<th>0-600 msec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SubSame-MinSame</td>
</tr>
<tr>
<td>theta (4-7Hz)</td>
<td>0.9 (neg)</td>
</tr>
<tr>
<td>alpha (8-12Hz)</td>
<td>0.67 (neg)</td>
</tr>
<tr>
<td>beta (13-30Hz)</td>
<td>0.62 (pos)</td>
</tr>
<tr>
<td>gamma (30-55Hz)</td>
<td>0.63 (pos)</td>
</tr>
</tbody>
</table>

Table 2. Results of the cluster-based random permutation tests for the substantial vs minimal change contrast, reported are the smallest p-values.

Power changes time-locked to the noun

Cluster-based random permutation test didn’t reveal any significant differences for any of the contrasts on the trials time-locked to the noun. For visualization (Figure 4), we chose to plot the dynamics of alpha power differences between substantial and minimal change conditions for both the same and another token reference because it was the only significant effect found on the determiner trials. The pattern of alpha dynamics for both reference conditions is qualitatively similar to that of the respective determiner trials; however, as has been mentioned already and is reported in Table 2, none of the comparisons on the noun trials yielded significant differences.
Power changes time-locked to the determiner: same token reference

Figure 2. Time-frequency representations for the (A) substantial and (B) minimal change conditions, as well as (C) the difference between the substantial and minimal change conditions for the same token reference. The data used for these graphs are an average of four representative channels (E69, E70, E74, E75) highlighted in (D) – the difference topography between the substantial and minimal change conditions averaged in the 8-12 Hz frequency and 80-510 msec time windows. (E) The dynamics of alpha (8-12 Hz) power changes. The color bars represent relative power change compared to the baseline period spanning from -600 to -250 msec before the determiner onset.
Power changes time-locked to the determiner: another token reference

Figure 3. Time-frequency representations for the (A) substantial and (B) minimal change conditions, as well as (C) the difference between the substantial and minimal change conditions for another token reference. The data used for these graphs are an average of four representative channels (E69, E70, E74, E75) highlighted in (D). Topographies in (D) and (E) are averaged for the alpha frequency band (8-12 Hz) to highlight the absence of effect found for the same token reference. The color bars represent relative power change compared to the baseline period spanning from -600 to -250 msec before the determiner onset.
Figure 4. The dynamics of alpha (8-12 Hz) power changes. The color bar represents relative power change compared to the baseline ([−600 -250] msec). The difference in activation between the substantial and minimal change conditions wasn’t significant.
DISCUSSION

In the present EEG study, we used neural oscillations to study how objects introduced into the discourse are tracked during sentence processing. We believe that as we comprehend language, these representations are retrieved from semantic memory, contextualized in the discourse, and maintained in short-term and episodic memory systems as language unfolds. We manipulated how many representations were associated with the same token: some scenarios described events which led to significant changes in the state of the object, thus more than one representation was now associated with the introduced token (before and after change); while other scenarios described events which didn’t result in object’s state change, thus one representation was sufficient. We also manipulated whether the same token or another token of the same type was later referred to in the discourse. This allowed us to compare the neural signatures of representing the same object token in its different states (the same onion before and after chopping) and several tokens of the same type in different states (e.g. one chopped and one intact onion) as well as to address the question whether simply having multiple state representations could lead to more effortful processing of the discourse or whether it is specifically retrieving the history of the same token and its multiple representations which increases the processing effort.

A time-frequency analysis of EEG, synchronized from the onset of the final determiner in the second sentence, revealed a significant increase in alpha power (8-12 Hz) in the substantial change condition relative to the minimal change condition when the sentence referred back to the same object token, but not when the sentence referred to
a different instance of an object (see Figures 2 and 3). How can the fact that we didn’t find alpha effect for another token reference help us interpret the findings of the present study? Conceptually, there is one major difference between processing that happens as one reads the final noun phrase which either refers back to the already mentioned item or introduces a new item of the same type. To illustrate this difference, let’s get back to the examples used in the Introduction,

1. The chef will chop the onion. And then, she will weigh the onion.
2. The chef will chop the onion. And then, she will weigh another onion.

In (1), processing the event of chopping the onion in the first sentence requires thinking about the onion before and after change, thus representations of the onion in both states are available. However, any further reference to this instance of an onion requires selection of one of these representations (given the context in (1), it should be the chopped onion) since they are mutually exclusive – the object can’t be in two different states simultaneously, unless we are talking about Schroedinger’s cat. Such clash of representations leads to competition, as demonstrated by increased activation in VLPFC in substantial compared to minimal change condition (Hindy et al, 2012; Solomon et al, 2015). In (2), representations of the initial and end states of the onion are also required to process the event of chopping, however the state of another onion introduced in the second sentence does not interfere with either of the states of the “old” onion, because their representations are not mutually exclusive and can coexist, thus no competition is elicited (as also demonstrated in Solomon et al (2015) – Stroop-sensitive voxels weren’t differentially activated in substantial and minimal change conditions whenever the second sentence introduced a new item). While fMRI studies mentioned above looked at the
Stroop-sensitive voxels and interpreted the difference between substantial and minimal change conditions in terms of competition between object-states, we can try to decompose the notion of competition into inhibition and selection components and interpret our EEG alpha effect as indicating inhibition of the irrelevant token state which is required for selecting the relevant one.

Since the initial discovery of alpha rhythms in the human EEG in 1920s and for a long time since then, increases in alpha have been associated with cortical idling, while alpha decreases were believed to support active information processing. However, since the more recent studies on memory load and retention found that alpha power increases proportionally to the amount of items that need to be retained in memory (e.g. Jensen et al., 2002; Tuladhar et al., 2007), the role of alpha oscillations for cognition has been reconsidered. While Jensen et al (2002) and Tuladhar et al (2007) studies examined alpha during the retention period, the study by Waldhauser, Johansson, & Hanslmayr, 2012 investigated oscillatory signatures of retrieval of competing visual memories, which is more directly relatable to the present study. Participants in their study were presented with abstract line drawings (cues) associated with rectangles of different colors (targets) presented to the right and left visual fields (RVF and LVF, respectively). Half of the shapes were paired with rectangles of the same color (non-interference condition), another half were paired with rectangles of different colors (interference condition). During the selective retrieval test phase the participants were presented with a cue and a white rectangular either in RVF or LVF and asked to covertly retrieve (imagine) the color of the box associated with that cue and visual field. EEG recorded during the selective retrieval
test was analyzed in the time-frequency domain and showed that there was an increase in alpha/beta power in the interference condition compared to the non-interference condition. When targets associated with the cue drawing were of the same color (non-interference condition), no such alpha/beta increase was observed. We believe that our object-states interference effect is similar in nature to this effect of interfering visual memories. A token which underwent a change of state has (at least) two distinct representations (and as a consequence, two distinct features sets associated with them) now bound to it, just like in the Waldhauser et al study, a cue in the interference condition is also associated with two representations differing on the color dimension. However, the study by Waldhauser et al had this additional visual field manipulation since they were interested in the lateralization of the effect. And indeed, the alpha/beta increase was found over the hemisphere associated with the competitor, and not the target item. They explain this finding in terms of the inhibition gating hypothesis formalized by Jensen and Mazaheri in their 2010 paper. According to this theory, information is gated by inhibiting the task-irrelevant areas of the brain, and this inhibition is implemented via alpha oscillations. For example, studies of spatial attention found increases in alpha over the hemisphere ipsilateral to the hemifield to which attention was directed (e.g. Thut, Nietzel, Brandt, & Pascual-Leone, 2006; Händel, Haarmeier, & Jensen, 2010). Taken together, these findings suggest that alpha is important for inhibition (of either competing memories or task-irrelevant regions), and this suppression of irrelevant information or brain areas facilitates processing of relevant information. If we reiterate this statement in the context of our study, suppression of irrelevant object-state facilitates activation of the relevant
one. However, the topography of our effect – which spans left fronto-temporal electrodes, right above VLPFC – doesn’t straightforwardly fit under the gating inhibition hypothesis if we believe that the alpha effect is reflective of the VLPFC effect reported in Hindy et al (2012) and Solomon et al (2015). Under Hindy and Solomon account, VLPFC is activated to a higher extent for processing competing object-states. Under the gating inhibition account, areas generating synchronized alpha oscillations are the ones which need to be inhibited for processing the critical information. If for a moment we assume that sensor-space is representative of the underlying brain space and that the alpha increase that we observe in the present study indeed has its sources in the left inferior frontal areas (based on the topography of the effect), then according to the gating inhibition hypothesis, these areas are inhibited to facilitate processing in other areas which might be more critical for our manipulation. It could be that our effect is not reflective of the VLPFC effect reported in earlier fMRI studies and thus this explanation would totally be possible. Or it could also be that our assumption that the observed topography reflects activation in VLPFC is wrong, which could very well be the case because (i) sensor space doesn’t map directly onto brain space and (ii) we didn’t run any additional analyses to localize out effect. To summarize the discussion we had so far, interference between multiple object-states should logically lead to inhibition of the irrelevant state, and alpha synchronization we observe in the substantial change condition might signal such inhibition given the previous findings connecting alpha and inhibition. Additional analyses are required to make a stronger connection between the EEG and fMRI findings.
We also found a marginally significant (p=0.07) decrease in beta (13-30 Hz) power at the determiner in the substantial change condition relative to the minimal change condition when the discourse introduced a new object token in the second sentence. As discussed in the introduction, beta activity is associated with maintenance of sentence-level meaning representation under construction and propagation of top-down predictions (Lewis and Bastiaansen, 2015): beta power increases as the sentence unfolds and decreases upon encountering a violation or any other cue signaling that the structure built so far must be reconsidered. Introducing a new token of the same type (as is the case of another token reference condition) could serve as such a cue to the comprehension system that the meaning built so far must be revised and the focus should be switched to the new token. Revising the meaning in the substantial change condition is perhaps more effortful simply because the representation of the event there has more detail than in the minimal change condition, and this fact could be reflected in decrease in beta in the substantial compared to minimal change condition. However, since this effect is marginal, we are not further discussing it here.

Analysis of filler items designed to elicit referential and lexical ambiguity didn’t yield any significant results (for the summary of results, see Appendix C). The pattern of activation associated with referentially and lexically ambiguous items didn’t resemble that associated with the object change manipulation. Thus, the results of the statistical analysis and visual inspection of the filler items suggest that interference resulting from multiple competing object-states representations is not the same as the interference
between multiple interfering antecedents for the pronoun or multiple meanings for the lexically ambiguous items.

While spatial resolution is not what people usually look for when using EEG, temporal resolution definitely is. Any assumptions about the timing of the fMRI effect reported by Hindy et al and Solomon et al was possible only because of comparing across several experiments. Using EEG in the present study allowed us to time-lock to the window of interest, specifically the last noun phrase in the second sentence, to directly test what happens at the retrieval. We found an effect at the determiner and no effect at the noun. We believe that this happened because of the nature of our stimuli set, where in 50% of all trials the noun in the second sentence was the same as in the first sentence (e.g. The chef will smell the onion. And then, she will weigh the onion.), which made it very easy for the participants to anticipate the ending of sentence pairs. Thus, the cloze probability of sentence endings was really high, not because of semantically restricting context of the sentence itself, but because of the frequent pattern in our stimuli. Under such conditions effect at the determiner is not surprising. And, in fact, there are studies (e.g. DeLong et al, 2005) demonstrating ERP effects at the articles preceding the critical words in contexts with high cloze probability of the final word.

EEG (unlike fMRI) also allows for exploration of the dynamics of the state-change effect. Figure 2E shows the dynamics of alpha power changes for the substantial vs minimal change contrast for the same token reference. We can see that the differences emerge first rather focally separately over the left and right hemispheres around 100 msec after the determiner onset; at around 300 msec they are distributed almost over the entire
scalp and at around 500 msec they are most pronounced over the left hemisphere. So far we’ve discussed only the effect over the left fronto-temporal channels because this is the area in the sensor space where the effect is most pronounced and it is over the regions that fMRI studies by Hindy et al (2012) and Solomon et al (2015) showed are involved in the resolution of the conflict between two representations of the same token. As was discussed earlier, this effect in the sensor space might (or might not) be representative of the VLPFC competition effect seen in earlier fMRI studies. How about the rest of the dynamics? Research on semantic memory (Barsalou, 1999) suggests that conceptual representations (of objects) are distributed across brain areas recruited for processing sensory and motor information associated with those concepts (e.g. internal representations of the onion include representations of its smell, shape, motoric affordances, etc). Moreover, such representations are dynamic and change as a function of our personal previous experiences with the object as well as the more recent and immediate context we encounter the object in (for a review, see Yee, 2017). Information about certain features of the object might become available earlier because the context highlights/primes those features, e.g. being a participant in an eye-tracking study which uses a visual world paradigm might make visual features (such as shape) more salient than non-visual features (such as function). It doesn’t mean that function information is not accessible, it just means that it becomes available later in the course of object recognition (Yee, Huffstetler, & Thompson-Schill, 2011). In our study, we modulated the context in which the target word appeared such that some contexts described events that lead to a change of state while others didn’t. Actions which lead to a change of state such
as *chop, crack, mash*, etc change not only how the object looks before and after change (e.g. imagine an intact and a chopped onion), but also, for example, its motoric affordances: think about how picking up an intact and a chopped onion would require different grasps or even actions. Or in our example of a chef acting upon an onion, chopping an onion highlights the smell feature more so than weighing it. Actions which don’t lead to a change of state, such as *smell, inspect, weigh* are more likely to focus our attention only on a single generic feature set of that object (as distinct from the multiple feature sets associated with the dynamics of the object’s changes in state). Even though we didn’t run any quantitative analysis to control for the number of dimensions on which the object changes (and thus, potentially, the number and type of features the context highlights), our intuition is that grounding the object in the context which describes a significant change of state systematically highlights more features than the minimal change context. This systematic difference might have an effect on the time-course and topography of EEG associated with the object recognition in the substantial and minimal change conditions: as features of the multiple state representations attempt to activate, features associated with the context-irrelevant state representation need to be inhibited which is reflected in the alpha dynamics.

To summarize, our study demonstrated the dynamics of neural response associated with a retrieval of a conceptual representation during sentence processing – a dynamic which couldn’t be detected in fMRI studies on which the present study is based. Future work will further examine such dynamics and ask more specific questions about its timing and neural sources. Specifically, the immediate follow-up analyses to this work
will look earlier in the sentence pair to examine the dynamics of neural response associated with building representations of objects when they are first introduced into the discourse and with their maintenance as discourse unfolds.
REFERENCES


APPENDIX A

Table A1. Summary of studies on theta, alpha, beta and gamma oscillations related to sentence processing and memory encoding and retrieval.

<table>
<thead>
<tr>
<th>Study</th>
<th>Paradigm</th>
<th>Theta</th>
<th>Alpha</th>
<th>Beta</th>
<th>Gamma</th>
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</thead>
<tbody>
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<td><strong>Sentence processing: syntax</strong></td>
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<tr>
<td>Bastiaansen, Van Berkum, Hagoort,</td>
<td>Gender and number agreement violation</td>
<td>Increase in response to violations</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>2002a</td>
<td></td>
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<tr>
<td>Bastiaansen, Van Berkum, Hagoort,</td>
<td>Sentence reading (RSVP)</td>
<td>Gradual increase as the sentence unfolded; increase in response to word onset (compared to the blank screen reference interval)</td>
<td>Lower alpha - increase in response to word onset (compared to the blank screen reference interval); in lower-2 alpha and upper alpha, a widespread power decrease</td>
<td>x</td>
<td>x</td>
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<tr>
<td>2002b</td>
<td></td>
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<tr>
<td>Bastiaansen, Magyari, &amp; Hagoort,</td>
<td>Word category violation</td>
<td>Linear increase in correct sentences</td>
<td>Decrease upon violation</td>
<td>Decrease upon violation</td>
<td>Decrease upon violation</td>
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<td>2010</td>
<td></td>
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<tr>
<td>Meyer, Obleser, &amp; Friederici, 2013</td>
<td>Short vs long argument –verb distances (tapping into the working memory load during sentence processing)</td>
<td>x</td>
<td>Increase during retention</td>
<td>Increase during retrieval (upon the verb)</td>
<td>x</td>
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<tr>
<td>Lewis, Lemhöfer, Schoffelen, &amp;</td>
<td>Gender and number agreement violation</td>
<td>Increase upon violation</td>
<td>x</td>
<td>Decrease upon violation</td>
<td>x</td>
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<td>Schriefers, 2016</td>
<td></td>
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<tr>
<td>Study</td>
<td>Paradigm</td>
<td>Theta</td>
<td>Alpha</td>
<td>Beta</td>
<td>Gamma</td>
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<tr>
<td><strong>Sentence processing: semantic and syntactic manipulations</strong></td>
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<tr>
<td>Davidson &amp; Indefrey, 2007</td>
<td>Phrase structure and number agreement violation, semantic anomaly</td>
<td>Increase in theta upon semantic violations</td>
<td>Decrease upon violation</td>
<td>Decrease upon violation</td>
<td>x</td>
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<tr>
<td>Kielar, Meltzer, Moreno, Alain, &amp; Bialystok, 2014</td>
<td>Verb tense violation, semantic anomaly</td>
<td>x</td>
<td>Decrease upon violation</td>
<td>Decrease upon violation</td>
<td>x</td>
</tr>
<tr>
<td>Kielar, Panamasky, Links, &amp; Meltzer, 2015</td>
<td>Semantic anomaly, syntactic anomaly</td>
<td>Increase (1-5Hz) upon both types of violations</td>
<td>Decrease upon violation (different topography for different manipulations)</td>
<td>Decrease upon violation (different topography for different manipulations)</td>
<td>x</td>
</tr>
<tr>
<td>Bastiaansen and Hagoort, 2015</td>
<td>Correct sentences (1), semantic (2) and syntactic (3) violations, syntactically correct-semantically meaningless (4), words in random order (5)</td>
<td>Increase upon semantic violation</td>
<td>x</td>
<td>Higher for 1 and 4 than for 5 throughout the entire sentence</td>
<td>Higher for 1 than for 4 and 5 throughout the entire sentence</td>
</tr>
<tr>
<td>Vignali, Himmelstoss, Hawelka, Richlan, &amp; Hutzler, 2016</td>
<td>Semantic anomaly, Random word order</td>
<td>Higher for structured sentences (compared to random order)</td>
<td>x</td>
<td>Decrease upon anomalous words</td>
<td>Increase in structured sentences (compared to random order)</td>
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<tr>
<td>Bastiaansen, Linden, Keurs, Dijkstra, &amp; Hagoort 2005</td>
<td>Open and close class words compared to the blank screen reference interval</td>
<td>Increase in response to both class of words, however only open class words elicited theta increase over left temporal electrodes</td>
<td>Decrease in response to words (as compared to fixation baseline)</td>
<td>Decrease in response to words (as compared to fixation baseline)</td>
<td>x</td>
</tr>
<tr>
<td>Study</td>
<td>Paradigm</td>
<td>Theta</td>
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<td>Rommers, Dijkstra, &amp; Bastiaansen, 2013</td>
<td>Literal and idiomatic contexts, within each they had correct, incorrect-related-in meaning and incorrect-unrelated conditions</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>Increase in response to the more semantically informative word, but only within the literal context; lower in correct idioms than in correct literal sentences</td>
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<tr>
<td>Wang, Zhu, &amp; Bastiaansen, 2012</td>
<td>High cloze, low cloze, semantic violation</td>
<td>Increase upon semantic violation</td>
<td>x</td>
<td>x</td>
<td>Increase in the high cloze condition, but not in the low cloze and violation conditions</td>
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<tr>
<td>Wang et al, 2012</td>
<td>Congruent and incongruent sentence endings</td>
<td>x</td>
<td>Decrease for incongruent over the left hemisphere</td>
<td>Decrease over the left hemisphere (correlated with the N400)</td>
<td>x</td>
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<td>Peña and Melloni (2012)</td>
<td>Spoken sentence comprehension in native and non-native languages</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>Gamma differentiates between native and non-native languages (semantic integration)</td>
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<td>Mante S. Nieuwland and Andrea E. Martin, 2017</td>
<td>Referential ambiguity (4 different studies)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>Increase in gamma in response to referentially coherent expressions compared to referentially problematic</td>
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<td>Hald, Bastiaansen, &amp; Hagoort, 2006</td>
<td>Semantic violation</td>
<td>Increase upon violation</td>
<td>x</td>
<td>x</td>
<td>Decrease upon violation</td>
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<tr>
<td>Study</td>
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<td>Penolazzi, Angrilli, &amp; Job, 2009</td>
<td>Semantic violation (verb selectional restrictions violated)</td>
<td>x</td>
<td>x</td>
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<td>Lower upon violations</td>
</tr>
<tr>
<td>Röhm, Klimesch, Haider, &amp; Doppelmayr, 2001</td>
<td>Reading, reading + semantic task (finding a superordinate category for the target word)</td>
<td>Theta power equal between conditions (conclusion: working memory)</td>
<td>Less alpha in the semantic task (conclusion: semantic processing)</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Bastiaansen, Jensen, Hagoort, 2008</td>
<td>Individual words (with auditory or visual semantic properties)</td>
<td>Increase to words (as compared to reference blank interval); topographic double-dissociation for aud and vis words</td>
<td>An early increase and subsequent decrease</td>
<td>Increase to words (as compared to reference blank interval)</td>
<td>x</td>
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<tr>
<td>Weiss, Rappelsberger, 1996</td>
<td>Abstract and concrete nouns</td>
<td>x</td>
<td></td>
<td></td>
<td>Beta coherence difference between abstract and concrete nouns</td>
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<tr>
<td>Weiss et al, 2000</td>
<td>Memory encoding and retrieval of abstract and concrete nouns</td>
<td>Higher coherence during the encoding of later recalled nouns; concrete nouns showed higher short-range coherence; abstract nouns correlated with higher long-range coherence.</td>
<td>x</td>
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<td>x</td>
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<tr>
<td>Study</td>
<td>Paradigm</td>
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<tr>
<td>Klimesch, Schimke, &amp; Schwaiger, 1994</td>
<td>Concept-feature pairs: 1. Semantic task – are the features congruent with the concept; 2. Episodic task – was the same concept-feature pair presented before?</td>
<td>Increase during the feature word presentation in the episodic task</td>
<td>Decrease during the feature word presentation in the semantic</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Klimesch, Doppelmayr, Pachinger, &amp; Russegger, 1997</td>
<td>Congruency (feature-concept) matching task - semantic, free association task – blend, cued recall task - episodic</td>
<td>x</td>
<td>Decrease in upper alpha during the semantic task (during the presentation of the second word)</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Klimesch, Doppelmayr, Schimke, Ripper, 1997</td>
<td>Studying a list of words (encoding) followed by a recognition task</td>
<td>Increase during the study phase to the words that will be later remembered, increase during the recognition phase to correctly recognized targets (no such increase to distractors and not-remembered targets)</td>
<td>In the lower alpha, decrease in response to items that later will be correctly remembered. In the upper alpha, increase to items that later won’t be correctly remembered (upper alpha – semantics)</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Jensen &amp; Tesche, 2002</td>
<td>Sternberg memory task</td>
<td>Increase with the number of items to be remembered</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Jensen, Gelfand, Kounios, &amp; Lisman, 2002</td>
<td>Sternberg memory task</td>
<td>x</td>
<td>Increase with the number of items stored in short-term memory</td>
<td>x</td>
<td>x</td>
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<td>Study</td>
<td>Paradigm</td>
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<td>Klimesch, Doppelmayr, Schwaiger, Auinger, &amp; Winkler, 1999</td>
<td>Memory search paradigm</td>
<td>x</td>
<td>Increase in upper alpha band in the highest memory demand cognition</td>
<td>x</td>
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<td>Klimesch, Doppelmayr, Russegger, &amp; Pachinger, 1996</td>
<td>Implicit memory paradigm</td>
<td></td>
<td>Increase during the encoding of those words which could be remembered in the later recall task</td>
<td>x</td>
<td>x</td>
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<td>Tuladhar, Huurne, Schoffelen, Maris, Oostenveld, &amp; Jensen, 2007</td>
<td>Sternberg memory task</td>
<td>x</td>
<td>Increase with memory load</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Waldhauser, Johansson, &amp; Hanslmayr, 2012</td>
<td>Selective cue-based memory retrieval</td>
<td>x</td>
<td>Increase in the interference condition</td>
<td>x</td>
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APPENDIX B

Gamma power difference for the substantial vs minimal change contrast

Trials time-locked to the determiner
Same object token

Trials time-locked to the determiner
Another object token
Figure B1. The dynamics of gamma (30-55 Hz) power changes. The color bars represent relative power change compared to the baseline period spanning from -600 to -250 msec before the determiner onset.
APPENDIX C

This appendix contains information about the preprocessing and analysis of filler items, as well as brief discussion of the results.

Preprocessing

Filler sentences (N=160) were designed to (i) elicit transient lexical and referential ambiguity effects and (ii) reduce predictability of the object in the second sentence (for the rationale, see above). Each participant saw forty filler items which contained a lexically ambiguous word in the second sentence and forty control sentences (e.g. *The woman will wash the floor. And then, she will unroll the runner/carpet*), as well as forty filler items that contained a referentially ambiguous pronoun and forty control sentences (*John/Daphne valued Edward because he was very knowledgeable*). Since we were interested in the effects of lexical and referential ambiguity, our time-windows of interest were time-locked to the ambiguous nouns and pronouns and their controls.

We redefined filler trials to include 850 msec before and 1260 msec after the noun/pronoun onset which would allow us to look at the power spectrum associated with the critical words in the time-window of 600 msec before and 1000 msec after the critical word (given the parameters of the time-frequency analysis). After removing the linear trend from the trials and running automatic artifact rejection, we eliminated participants (N=9) who had more than 50% of trials with activity exceeding the +/-100 mV threshold. Approximately 16% of trials were removed from the data of the 22 participants who entered the final analysis.
Time-frequency analysis and cluster-based random permutation test

Parameters for the time-frequency analysis and permutation test were identical to those used for experimental items. The following comparisons were made:

- Lexically ambiguous vs unambiguous (LexAmb)
- Referentially ambiguous vs unambiguous (RefAmb)

Results

The cluster-based random permutation test didn't reveal significant differences between the lexically/referentially ambiguous and unambiguous items in any of the frequency bands.

<table>
<thead>
<tr>
<th></th>
<th>LexAmb</th>
<th>RefAmb</th>
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<tbody>
<tr>
<td>0.0-1000 msec</td>
<td></td>
<td></td>
</tr>
<tr>
<td>theta (4-7Hz)</td>
<td>no clust</td>
<td>0.73 (neg)</td>
</tr>
<tr>
<td>alpha (8-12Hz)</td>
<td>0.25 (pos)</td>
<td>0.91 (pos)</td>
</tr>
<tr>
<td>beta (13-30Hz)</td>
<td>0.56 (pos)</td>
<td>0.85 (pos)</td>
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</tbody>
</table>

Table C1. Results of the cluster-based random permutation tests for the lexically ambiguous vs unambiguous and referentially ambiguous vs unambiguous contrasts, reported are the smallest p-values.

Alpha power
(8-12 Hz)

A. Lexically ambiguous - unambiguous

B. Referentially ambiguous - unambiguous

Figure C1. The dynamics of alpha (8-12 Hz) power changes. The color bars represent relative power change compared to the baseline period spanning from -600 to -250 msec before the determiner onset.
Discussion

We believe that we didn't find significant effects in the analysis of lexically ambiguous items because the contexts in which ambiguous words were used were strongly biasing towards the intended meaning (thus all other meanings were highly unlikely). The reason we didn't find significant effects in the analysis of referentially ambiguous items is similar: we chose verbs which had a strong bias either towards actor (NP1) or patient (NP2) interpretation.