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The Role of Dynamic Frequency Synchrony in Syntactic Processing

DISSERTATION

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for the degree of

DOCTOR OF PHILOSOPHY

in Psychology (Cognitive Sciences)

by

Jessamy Norton-Ford Almquist

Dissertation Committee:
Professor Lisa Pearl, Chair
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Professor Greg Hickok

2015

DEDICATION

To my husband Zack.
For all of your love, support and steadfast encouragement.
You are a true partner, and the best one I could ask for.

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ABSTRACT OF THE DISSERTATION

The Role of Dynamic Frequency Synchrony in Syntactic Processing

By

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Doctor of Philosophy in Psychology (Cognitive Sciences)

University of California, Irvine, 2015

Professor Lisa Pearl, Chair

Currently, the most widely-used method in electrophysiological linguistic research involves grand-averaging of brain responses across trials and subjects a technique designed to overcome the low signal-to-noise ratio of the brains electrical response to a stimulus. Results of this technique (event-related potentials, or ERPs) have uncovered several reliable responses to linguistic variables, including responses to anomalous syntactic (left anterior negativity, or LAN, P600) and semantic items (N400). Psycholinguistic and neurolinguistic researchers often infer the functional significance of ERPs from their eliciting conditions, however in many cases a single category of representation cannot explain all occurrences. This work is an examination of several linguistically-distinct conditions which traditionally elicit only a limited number of syntax-related ERPs (LAN, P600), from the perspective of event-related changes in induced frequency synchrony. Induced activity represents part of the multidimensional EEG signal that is removed in the ERP grand-averaging process, namely oscillatory activity which is not phase-locked to the stimulus. Modulations in phase asynchronous oscillations reflect local changes in neural activity which control the frequency components of ongoing EEG (Pfurtscheller & da Silva, 1999), and are a critical component of the characterization of dynamics in the frequency signal. Frequency synchrony is of interest to theories of sentence processing given its long-established association with the binding of elements into complex representations (Gray et al., 1989a) and given that it has been argued to facilitate activity

of spatially-distant, functionally-connected networks (e.g., Singer, 1993). Furthermore, recent work by (Bastiaansen et al., 2010) has revealed the role of certain frequency activity in syntactic (Beta) and more general sentence processing (Theta). Results of the work presented here indicate that a variety of grammatical processes occur within the time windows of the LAN and P600, including top-down creation of filler-gap relations (primarily reflected in early increases in Theta band activity), processing of complex syntactic representations (primarily reflected in increases in Beta band activity) and evaluative processes which reflect the probability of a (syntactic) event (reflected in corresponding decreases in Alpha and Beta activity in late processing windows). Overall, this work supports a theory in which the LAN and P600 are not single events in grammatical processing, and provides hypotheses about the role of certain frequency activity during sentence processing which can be examined in subsequent confirmatory research.

Chapter 1

Introduction

Currently, the most widely-used method in electrophysiological linguistic research involves *grand-averaging* of brain responses across trials and subjects – a technique designed to overcome the low signal-to-noise ratio of the brain's electrical response to a stimulus. According to proponents of the method, such 'noise' (which can be intrinsic or extrinsic in nature) varies randomly with respect to the time point of stimulation, and is therefore reduced by the averaging process (any two waves of identical frequency and amplitude will average to zero if they are 180 degrees out-of-phase with one another). What results is a *time-locked* average which includes only *phase-locked* information, known as an *event-related potential* (ERP). ERPs represent dynamic changes in amplitude following the onset of a stimulus, and offer linguists, psychologists and neuroscientists (indirect) fine-grained temporal information about language processing mechanisms.

Generally speaking, psycho- and neurolinguistic researchers infer the functional significance of an ERP from its eliciting conditions. The larger category of these conditions is often thought to be indicative of the level of *representation* or the type of *processes* the ERP is relevant to, though the nature of this "category" can often be elusive. The event-related potential (ERP) known as the P600 (Osterhout & Holcomb, 1992) or the 'Syntactic Positive Shift' (SPS; Hagoort et al., 1993) is a perfect demonstration of this fact. The P600 is a broad posterior sustained positivity which (prototypically) arises approximately 600ms after stimulus-onset and has been found in response to ungrammaticalities such as phrase structure violations (Neville et al., 1991; Osterhout & Holcomb, 1992) and island violations (McKinnon & Osterhout, 1996), misanalyses of grammatical syntactic structure (e.g., garden path sentences like Bever (1970)'s famous: *The horse raced past the barn fell*; Osterhout & Holcomb, 1992), and completion of grammatical long-distance dependencies (e.g., object- vs. subject-relative clauses; Phillips et al., 2005). Initially, the P600 was referred to as an index of "syntactic reanalysis" (Osterhout & Holcomb, 1992); more recently it has been described as a reflection of "general syntactic integration difficulty" (Kaan et al., 2000). Interestingly, the P600 has also been found in response to apparently *semantically* anomalous sentences (e.g., *For breakfast the eggs would only eat toast and jam*; Kuperberg et al., 2003; *The hearty meal was devouring the kids*; Kim & Osterhout, 2005). The unique circumstances under which this 'Thematic P600' (Stroud, 2008) is elicited are not so obviously within the scope of "syntactic integration difficulty," and this fact has fueled debate as to whether its presence in such sentences (and the co-occurrent, conspicuous absence of the ERP known to index difficulty in semantic processing – the N400; Kutas & Hillyard, 1980) is evidence for independent semantic and syntactic analyzers. According to this perspective, the P600 reflects an overall mismatch in the otherwise valid outcomes of the semantic and syntactic streams (Kim & Osterhout, 2005; van Herten et al., 2005; Kuperberg, 2007; Bornkessel-Schlesewsky & Schlesewsky, 2008), a claim which is in dispute by proponents of a more "integrated" parser (Stroud & Phillips, 2012). In short, despite being best-known for its correlation with difficulties in syntactic processing: (i) the P600 has also been found following *successful* dependency resolution and (ii) in limited instances also appears to be influenced by *semantic* information.

Another example of elusive categorization is found in the case of the ERP known as the *left* *anterior negativity* (LAN; Neville et al., 1991; Kluender & Kutas, 1993a,b; Osterhout & Mobley, 1995). This component, named for its prototypical topography, is a negative deflection which peaks approximately 300-500ms following a wide-range of agreement errors including subject-verb agreement violations (Kutas & Hillyard, 1983) and case violations (e.g., **The plane took we to paradise and back*; Coulson et al., 1998). An *early* version of the LAN (100-300ms latency) known as the ELAN has also been found in response to a narrow sub-class of morphologically-salient phrase structure violations (e.g., *…*Joe's of stories Africa*; Neville et al., 1991). Though the functional significance of the LAN has yet to be fully settled, its relative timing among other well-known components has led some to propose a *syntax-first* architecture for language processing (Friederici, 2002). According to this architecture, subtypes of syntactic information are processed in a specific, serial order (represented by the ELAN and the LAN, respectively) and either entirely precede or occur simultaneous with the processing of semantic information. In this architecture, an occurrence of the ELAN represents a failure in the processing of phrase structure information (which occurs prior to semantic processing), and the LAN a broader set of failures in morphosyntactic processing. This proposal remains controversial, and as it turns out only captures the facts of a *subset* of the eliciting conditions of the canonical LAN – namely those of the 'morphosyntactic LAN' (Fiebach et al., 2002). In addition to morphosyntactic conditions, the LAN has also been found following *wh-fillers* and *gaps* in long-distance dependencies, namely object-relative clauses vs. subject-relatives (Kluender & Kutas, 1993b) or *whether* clauses (Kaan et al., 2000). Noticeably, these LAN-eliciting *wh*-dependency conditions are absent from syntax-first accounts, and in fact an independent, complementary line of research currently exists for such cases. According to these researchers, the LAN found in response to *wh*-dependencies reflects the taxation of *working memory* (Kluender & Kutas, 1993a,b; King & Kutas, 1995; Kluender & Münte, 1998; Fiebach et al., 2001, 2002), which accurately predicts that short-distance dependencies will not elicit LANs and that long-distance dependencies (in which an item must be stored and held) will. These are known as instances of the 'working memory'

LAN (Fiebach et al., 2002).

The apparent synchronicity of eliciting conditions in the case of the P600 and the LAN poses serious questions for researchers, including (1) whether the mechanism(s) underlying these ERPs are in some way *meta-categorical* (with respect to linguistic categories) and therefore act upon more than one category of representation. For example, it has been proposed that the P600 represents an *integration* process, which necessarily operates on more than one linguistic category of information at a time. In addition, the LAN has been characterized as representing the even more domain-general process of working memory, which will be relevant to many if not all linguistic domains – not just to one. Another question researchers should consider is (2) whether physiological evidence of the brain's response garnered from *ERP methodology* can ever perfectly correlate with linguistic categories of representational information.

This work is a test of whether additional analysis techniques applied to event-related data can effectively supplement methods currently used to induce linguistic mechanisms. More specifically, this work examines whether a representation of electrophysiological responses to linguistic conditions according to dynamic *frequency* information agrees with or differs from our understanding based on dynamic amplitude information (provided by ERPs), and whether a comparison of the two representation-types can further our understanding of the mechanisms involved in processing linguistic representations. For example, if such an alternative technique were to uncover qualitative differences in brain responses between conditions which elicit the same ERP, then this would be evidence consistent with distinctive mental representations or processes underlying a single ERP response. Put another way, this would be evidence that ERP methods may be too course-grained to uniquely identify the linguistic representations/processes involved in such cases. If, on the other had, such an alternative analysis was consistent with ERP evidence and found no significant differences between the conditions, then this would be additional evidence consistent with common representations or mechanisms underlying the response in both cases. Furthermore, correlations within the frequency spectrum may offer insight into the number/nature of the processes underlying the event-related EEG. Similar work by Bastiaansen and Hagoort has revealed correlations of working memory use with theta band activity (Bastiaansen & Hagoort, 2003, 2006), as well as correlations of increases in theta (Bastiaansen et al., 2002) and disruptions in beta band activity (Bastiaansen & Hagoort, 2006; Bastiaansen et al., 2010) during the processing of syntactic violations.

The first two experiments of my dissertation are surveys of a broad set of syntactic manipulations known to elicit a small number of ERPs – namely, the LAN and P600. Experiment 1 of this work examines and compares the dynamic frequency information of a number of (potentially) LAN-inducing and P600-inducing syntactic and morpho-syntactic conditions including: (1) case violations, (2) verb agreement violations, (3) θ-criterion violations. The violation in condition (1) represents a morphological mismatch within the *Case* system of English (e.g., a pronoun with nominative case in an object position, where accusative case is assigned, such as **I like they.*). The violation in condition (2) represents a morphological mismatch within the (verb) *Agreement* system of English (e.g., a progressive morpheme *-s* appended to a verb following a modal auxiliary, such as ... **will walks*). Finally, the violation in condition (3) represents a phrase-structure level violation of the *Theta Criterion*, which demands that all verbal arguments be syntactically realized (once, and only once), by omitting the object of a transitive verb (e.g., **They would honor before the fireworks.*). These three conditions offer representations of three known syntactic systems, which may be uniquely encoded in neural networks or which may to a large extent overlap. Further, a comparison of conditions (1) and (2) with condition (3) will test the homogeneity of the brain's response to morpho-syntactic and "deeper" syntactic processes.

Experiment 2 examines a set of P600-inducing conditions that are not exclusively *syntactic*: (1) garden path sentences, (2) (certain) island violations, (3) phrase structure violations, and (4) Thematic P600s. The grammatical violation in condition (1) represents a violation of syntactic *prediction* (e.g., a passive relative clause with no overt complementizer where a NP object is predicted, as in **The broker persuaded to conceal the transaction went to jail.*). Violations of conditions (2) are known as *Island violations*, in that they represent a dependency that extends into a clause which cannot accommodate a dependency (hence the island metaphor). These violations are to a certain extent idiosyncratic and are not yet well-understood as a single phenomenon, but are syntactically defined (*dependencies*, *clause-boundaries*) and include adjunct clauses (e.g., clauses head by *when* such as **I wonder who the candidate was annoyed when his son was questioned by.*). Condition (3) represents a violation of "deep" syntax or phrase structure (e.g., **Frank's about speech migrants was successful.*). Finally, violations of condition (4) are those controversial violations that appear almost semantic in nature, but which do not elicit the expected N400 and, rather, elicit a P600. These include sentences in which an inanimate subject appears (which are most commonly Experiencers or Patients, thematically speaking) followed by verbal morphology indicating it as the Agent or "do-er" of the sentence (e.g., *#The investigator believed that the murder was witnessing the three bystanders.*). Taken together, these stimuli will allow for comparisons of syntactic violations (e.g., conditions 2 and 3), potentially integration-based errors (condition 4), and misanalyses of (and recovery from) misleading syntactic structure (condition 1).

Comparing the dynamic frequency responses to the conditions of Experiment 1 and Experiment 2 can tell us more about whether the electrical activity of the brain (as we have accessed it) provides unique representations of grammatical processes (which are well-established, both behaviorally and logically, in linguistic research), or whether, much like event-related activity dynamic frequency synchrony accesses a larger category of processes – one which encompasses a variety of linguistic conditions.

1.1 The left anterior negativity (LAN)

The event-related potential commonly known as the left-anterior negativity (LAN) represents a relative increase in negativity that (prototypically) peaks 300-500ms post stimulus-onset in left-lateralized, anterior sensors (Kluender & Kutas, 1993a).

1.1.1 Morphosyntactic Violations

The LAN has been found following a variety of grammatical errors, including a wide variety of agreement violations (e.g., Kutas & Hillyard, 1983; Hagoort & Brown, 2000), phrase-structure violations (e.g., Neville et al., 1991), subcategorization violations (e.g., Rösler et al., 1993) and case violations (e.g., Münte et al., 1993; Coulson et al., 1998). These conditions have been grouped together under the umbrella of morphosyntactic violations, leading some to refer to the response in these cases as the 'morphosyntactic LAN' (Fiebach et al., 2002).

Agreement Violations

SUBJECT-VERB agreement violations

Number: Kutas & Hillyard (1983); Hagoort et al. (1993); Osterhout & Mobley (1995); Coulson et al. (1998); Hagoort & Brown (2000); Angrilli et al. (2002); Kaan (2002); De Vincenzi et al. (2003); Palolahti et al. (2005); Roehm et al. (2005); Silva-Pereyra & Carreiras (2007).

1. a. As a turtle grows it's shell grows too.
   b.*As a turtle grows it's shell grow too. (LAN)
   c. Some shells are even soft.
   d.*Some shells is even soft. (LAN)

(Kutas & Hillyard, 1983)

2. a. Het verwende kind gooir het speelgoed op de grond.

The spoiled child throws the toy on the ground.

b.*Het verwende kind gooien het speelgoed op de grond. (LAN)

The spoiled child throw the toy on the ground.

(Hagoort et al., 1993; Hagoort & Brown, 2000)

3. a. The elected officials hope to succeed.

b.*The elected officials hopes to succeed. (LAN)

(Osterhout & Mobley, 1995)

4. a. Every Monday he mows the lawn.

b.*Every Monday he mow the lawn. (LAN)

c. They sun themselves on the beach.

d.*They suns themselves on the beach. (LAN)

(Coulson et al., 1998)

5. a. Il vecchio cameriere serve con espressione distratta.

The old waiter serves with (an) inattentive expression.

b.*Il vecchio cameriere servono con espressione distratta. (LAN)

The old waiter serve with (an) inattentive expression.

(Angrilli et al., 2002; De Vincenzi et al., 2003)

6. a. Hoewel volgens het gerucht de keizer de dissident zal gaan verbannen...

Although the emperor $will_{sg}$ *ban the dissident according to the rumor...*

b.*Hoewel volgens het gerucht de keizer de dissident zullen gaan verbannen... (LAN)

Although the emperor $will_{pl}$ *ban the dissident according to the rumor...*

(Kaan, 2002)

7. a. Suuri kimalainen surisee kukkien keskellä.

A big bumblebee buzzes among the flowers.

b.*Suuri kimalainen surisevat kukkien keskellä. (LAN)

A big bumblebee buzz among the flowers.

(Palolahti et al., 2005)

8. a. Den Auftrag bearbeiten sie dennoch nicht.

They [do] not execute the order yet.

b.*Den Auftrag bearbeiten er dennoch nicht. (LAN)

He [do] not execute the order yet.

(Roehm et al., 2005)

9. a. Yo entiendo la idea.

$I_{1p,sg}$ $understand_{1p,sg}$ *the idea.*

b.*Nosotros entiendo la idea. (LAN)

$We_{1p,pl}$ $understand_{1p,sg}$ *the idea.*

(Silva-Pereyra & Carreiras, 2007)

Person: Hinojosa et al. (2003); Silva-Pereyra & Carreiras (2007).

10. a. La prueba ocultada por el fiscal aparecío.

The proof (that was) hidden by the public prosecutor $appeared_{3p,sg}$.

b.*La prueba ocultada por el fiscal aparecí. (LAN)

**The proof (that was) hidden by the public prosecutor* $appeared_{1p,sg}$.

(Hinojosa et al., 2003)

11. a. Yo entiendo la idea

$I_{1p,sg}$ $understand_{1p,sg}$ *the idea.*

b.*Tú entiendo la idea (LAN)

$You_{2p,sg}$ $understand_{1p,sg}$ *the idea.*

(Silva-Pereyra & Carreiras, 2007)

Gender: (12) Hagoort & Brown (1999).

12. a. De kapotte <u>paraplu</u> staat in de garage.

    The$_{com}$ broken <u>umbrella</u>$_{com}$ is in the garage.

    b.*Het kapotte <u>paraplu</u> staat in de garage. (LAN)

    The$_{neut}$ broken <u>umbrella</u>$_{com}$ is in the garage.

DETERMINER-NOUN agreement violations

Number: (13) Kutas & Hillyard (1983);

13. a. All turtles have four <u>legs</u> and a tail but some have very different feet.

    b.*All turtles have four <u>leg</u> and a tail but some have very different feet. (LAN)

Gender: (14) Gunter et al. (2000);

14. a. Sie bereist das <u>Land</u> auf einem kraftigen Kamel.

    She travels the$_{neuter}$ <u>land</u>$_{neuter}$ on a strong Camel.

    b.*Sie bereist den <u>Land</u> auf einem kraftigen Kamel. (LAN)

    She travels the$_{masc}$ <u>land</u>$_{neuter}$ on a strong Camel.

For a review, see Molinaro et al. (2011).

Subcategorization Violations

15. a. Der Präsident wurde <u>begrüβt</u>.

    The president is being greeted.

    b. *Der Lehrer wurde <u>gefallen</u>. (LAN)

    **The president is being fallen.*

(Rösler et al., 1993)

Phrase Structure Violations

16. a. The man admired Don's sketch of the landscape.
    b. *The man admired Don's of sketch the landscape. (LAN)

(Neville et al., 1991)

Case Violations

17. a. Der Zollbeamte kontrolliert den Koffer.
    **The customs officer controls the suitcases.*
    b. *Der Zollbeamte kontrolliert die Koffer. (LAN)
    **The customs officer controls the suitcase's.*

(Münte & Heinze, 1994)

1.1.2 Wh-dependencies

The LAN has also been found in response to *wh*-dependencies. In 1993, it was discovered following *fillers* and *gaps* in object-relative clauses compared with subject relative clauses (Kluender & Kutas, 1993a, 18). In several cases this negativity has been sustained between the filler and the gap (King & Kutas, 1995; Kluender & Münte, 1998; Fiebach et al., 2001, 2002; Felser et al., 2003), though recent work has localized the source of the negativity to the first few words following the filler (Phillips et al., 2005). In addition, anterior negativities have been seen in response to *wh*-in-situ items in Japanese (Ueno & Kluender, 2009, 19).

wh-dependency

18. a. *subj-dep*: Couldn't you decide who should sing something for Grandma at the reunion?

    b. *obj-dep*: Did he wonder who he could coerce into signing this time? (LAN)

(Kluender & Kutas, 1993a)

wh-in-situ dependencies

19. a. Calvin-ga pizza-o mottekita-ndesu-ka

    Did Calvin bring pizza?

    b. wh-in-situ: Calvin-ga nani-o mottekita-ndesu-ka (LAN)

    What did Calvin bring?

(Ueno & Kluender, 2009)

1.1.3 Variability in the LAN

While the LAN has been consistently associated with various morphosyntactic and dependency-related components of sentence processing, there are many cases in which the LAN has not been detected in response to these same conditions.

Topography

While the LAN is best-known as a left *anterior* brain response, negativities in response to syntactic manipulations have been found in a wide-range of topographical locations within the 300-500ms post-stimulus latency window. Several studies have found more *central* versions of the response, including more central negativities in response to incorrect verb tense (20), and more centro-*parietal* negativities in response to case inflection errors in German (17) and subject-verb agreement errors (21). *Posterior* negativities have also been found in response to short-distance dependencies (22).

Incorrect Verb Tense

20. a. Ice begins to grow.

    b. *Ice begins to grew. (LAN)

(Kutas & Hillyard, 1983)

Subject-Verb Agreement Errors

21. a. Every Monday he mows the lawn.

    b. *Every Monday he mow the lawn. (LAN)

(Coulson et al., 1998)

Short-distance Dependencies

22. a. −*dependency*: The detective hoped that the lieutenant knew that the shrewd witness would recognize the accomplice in the lineup.

    b. +*dependency: The detective hoped that the lieutenant knew which accomplice* the shrewd witness would recognize in the lineup. (LAN)

(Phillips et al., 2005)

While the LAN is named as a *left*-lateralized negativity, a bilateral yet primarily *right*- lateralized anterior negativity (RAN) has been found following subject-verb agreement errors (21) and *wh*-in-situ items in Japanese (19). Furthermore, bilateral negativities have also been found in response to sentences containing an incorrect noun number (13) and incorrect person agreement (10). Bilateral *early* negativities (ELANs) have also been found in response to phrase structure violations (Knösche et al., 1999, 23).

Phrase Structure Violations

23. a. Die Kuh wurde im Stall gefuttert.

The cow was in the stable fed. [literal translation].

b. *Die Gans wurde im gefuttert. (LAN)

The goose was in the fed. [literal translation].

(Knösche et al., 1999)

Latency

The latency of the (E)LAN depends on several stimulus and experiment-specific factors. To begin, phrase-structure violations involving overt morphological marking are the only violation-type which consistently elicit *early* left anterior negativities (Neville et al., 1991, 16). Furthermore, whether a word's category-identifying morphology occurs early or late in the word will affect the latency of the LAN (i.e., *prefix* vs. *suffix* morphology; Friederici et al., 1993). Therefore, if a word whose category represents a phrase structure violation is identifiable as such by its prefix morphology, it will likely be followed by an anterior negativity with shorter latencies than would the same word if it was identifiable by its suffix morphology.

Modality

In addition, the mode of presentation of the stimulus matters; auditory presentation is more conducive to early-latency LANs (ELANs) than visual presentation, though both modes will elicit LANs (auditory: Friederici et al., 1993; visual: Kluender & Kutas, 1993a). For example, an auditorily presented word (in connected speech) whose category is identified in its prefix elicits an ELAN with peak amplitude between 120-200ms (Friederici et al., 1996; Hahne & Friederici, 1999). In the visual domain, words must be presented at a very rapid pace in idealized high-contrast conditions in order to elicit such early negativities (Gunter & Friederici, 1999). If words are presented visually at a slower rate (Münte et al., 1993), or under lower-contrast conditions (Gunter & Friederici, 1999), the negativities elicited will have more traditional peak amplitude latencies (300-500ms).

1.1.4 Functional Significance of the LAN: Proposals

The LAN as a reflection of morphological processing. For years, sentence-processing theories have debated the order and manner in which linguistic information is processed during comprehension. Proponents of *interactive* or *constraint-satisfaction* models claim that all available aspects of linguistic information interact during all stages of language processing (Marslen-Wilson, 1987; McClelland et al., 1989), whereas proponents of *serial*, or *syntax-first* models of language processing argue for the early, automatic, autonomous processing of certain syntactic information prior to the processing of semantic information (Frazier & Fodor, 1978; Frazier, 1987). According to a recent influential *syntax-first* model by Friederici, the ELAN reflects failures in this earliest phase of language processing (100-300ms post stimulus-onset), in which word category information is used to build initial phrase structure. Following this is a second stage of processing, in which 'structural and thematic relations are assigned' (Friederici & Meyer, 2004). Within this stage (300-500ms) are two independent, simultaneous streams of information processing, reflected by the LAN and the N400, respectively. The LAN reflects disruptions in the building of structural relations based on morphosyntactic information and the N400 reflects the building of thematic relations based on available lexical-semantic information. These streams are integrated in a third and final stage of processing (500-1000ms), during which any required repair or reanalysis for the facilitation of this integration will lead to a P600. This account, of course, only refers to evidence of the 'morphosyntactic LAN' (Fiebach et al., 2002), which is elicited based on a variety of morphosyntactic violations (see Section 1.1). Furthermore, whether the latencies of these ERPs truly reflects a segregation in processing streams remains an open question.

The LAN as a reflection of working memory processes. LANs associated with long-distance dependencies are often thought to represent increases in working memory load. Kluender & Kutas (1993a) explain the presence of LANs following fillers and gaps in object-relative (and *not* subject-relative) clauses as consequences of working memory requirements associated with *storage* and (later) *reactivation/integration* of a filler, both of which are only required in the case of *long-distance* dependencies. According to their account, on-line processing of object-relative clauses such as *The man*$_i$ *who John kicked* ___$_i$ *went home* require that a filler (in this case, *who*) be stored in working memory until its corresponding gap is encountered (in this case, the absence of a direct object for the verb *kicked* indicated by the presence of the verb *went*). The necessity of this storage becomes apparent to a reader/listener as they encounter the embedded subject NP *John* following the relative clause NP head *who*, and, as a result, a LAN is generated. Furthermore, in order for the object relative clause dependency to be completed, the stored item must be reactivated in memory, specifically at the point at which one encounters the gap. No such storage or reactivation is necessary in a subject relative case like *The man*$_i$ *who* ___$_i$ *kicked John went home*, as the word immediately following the filler (in this case, the verb *kicked*) is indicative of the gap having already passed. Kluender & Kutas's claims are consistent with a line of memory research attributing working memory cost to *storage* and *integration* processes (Baddeley, 1990; Just & Carpenter, 1992; Anderson et al., 1994; Lewis, 1996).

This notion of a 'working memory LAN' (Fiebach et al., 2002) has been further strengthened by accounts of its sustained nature. Its negativity is maintained across a dependency (King & Kutas, 1995; Fiebach et al., 2002; Phillips et al., 2005), which King & Kutas argued could represent the use of working memory resources to *maintain* a filler in memory. [1] Several

[1]Work with macaque monkeys performing simple delayed-response tasks has found both sustained individual cell activity within dorsolateral prefrontal cortex and negative slow potentials at the level of the scalp

sentence processing accounts have made similar claims of inherent sustained or accumulated processing costs in long-distance-dependencies which are imposed on limited available computational resources (for reviews, see: Tanenhaus & Trueswell, 1995; Gibson & Pearlmutter, 1998). Dependency Locality Theory (Gibson & Pearlmutter, 1998; Gibson, 2000) attributes the relative increase in cost to an accumulating need for resources as additional referents are encountered across a dependency. Other accounts attribute the cost to parsing strategies, such as the *Active Filler Strategy* (Frazier, 1987) in which the parser attempts to resolve dependencies (by creating a gap) as soon as a *wh-* phrase is encountered, or strategies which link *wh-* phrases to the first verb the parser encounters, in hopes that the verb will assign the phrase its thematic role (Aoshima et al., 2004; Gibson et al., 1994; Pritchett, 1991). Claims of a distance sensitivity underlying the LAN have been contradicted in work by (Phillips et al., 2005), where the source of the sustained negativity has been localized to within the first few words that follow the *filler*.

In their 2001 paper, Vos et al. propose the LAN as a reflection of the "working memory processes involved in the detection of [an] actual violation and gap-filling processes," (pg. 21). This account unifies LANs found in response to morphosyntactic violations and *wh-* dependencies, as they are both indicative of working memory use. As an example, according to Vos et al. subject-verb agreement (and its violation) requires that a subject's *number* feature be kept activated in memory until it can be checked against the verb (24).

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while the monkeys held information in memory (reviewed by Goldman-Rakic, 1987; Koch & Fuster, 1989).

Number Agreement Violations (Subject-Verb)

24. a. De toeristen die een druk programma hebben, <u>bezoeken</u> het theater dat heel beroemd is.

    The tourists that a busy schedule have, visit the theater that very famous is.

    [literal translation]

    b. *De toeristen hebben een druk programma en <u>bezoekt</u> het theater dat heel beroemd is. (LAN)

    The tourists have a busy schedule and <u>visits</u> the theater that very famous is.

    [literal translation]

(Vos et al., 2001)

In (24), the authors argue that the *number* feature of the matrix subject *De toeristen* (plural) must be maintained across five words (*hebben een druk programma en*) in order to reach the verb *bezoekt*. At this point the parser can detect a mismatch in the *number* features of the subject (plural) and verb (singular), and can respond to the violation. In this approach, the LAN that is measured at the point of the violation is a reflection of the accumulated increase in working memory load, which has been developing from the point of initiation of the dependency (in this case, the NP subject). Vos et al. (2001)'s proposal offers an explanation for studies which have found only a P600 (no LAN) in response to short-distance subject-verb agreement errors, such as those seen in Osterhout & Mobley (1995; 3).

Potential counter-examples to Vos et al. (2001)'s proposal are indicated in both EEG and behavioral evidence, beginning with (admittedly, atypically posterior) LAN-like negativities found in response to short-agreement relations in Coulson et al. (1998; 21). In addition, asymmetric delays in reaction times from Wagers 2009 offers evidence against a maintenance approach. Wagers et al. (2009) compared agreement violations (25) in which an object-relative clause head NP matches (in number) the embedded clause verb, which in turn does not match the embedded clause subject. This allows a superficial agreement of the embedded clause object (here displaced to the object-relative head position) and the verb, while the embedded subject and verb do not agree. Wagers et al. (2009) found that reaction times were delayed in the agreement violation cases, whereas control sentences in which the object-relative head NP *and* the embedded subject NP *both* matched (in terms of number) the embedded verb. In such a case, if the plurality of the dominant NP was stored and maintained for a later potential agreement relation (leading to a LAN), delays should be visible in both cases while the object-relative NP is held in memory until the occurrence of the embedded clause verb. Rather, the asymmetry in which the ungrammatical sentences have longer reaction times indicates that a *retrieval* (rather than a maintenance) process is occurring, at the point at which the embedded clause verb is encountered.

Number Agreement Violations (Embedded Subject-Verb)

25. a. The musicians who the reviewer praises so highly will probably win a Grammy.
    b. *The musicians who the reviewer praise so highly will probably win a Grammy. (LAN)

(Wagers et al., 2009)

The LAN as "a correlate of active syntactic expectations" In a review of the ERP literature dealing with agreement violations, Molinaro et al. (2011) finds that, on the whole the LAN is elicited in cases where violations involve overt morphological marking (e.g., **They walks to the store* vs. **She walk to the store*). As a result, Molinaro et al. (2011) proposes "the LAN is the correlate of active syntactic expectations for a morphosyntactically related constituent," representing an "active predictive process based on relevant syntactic information (such as surface cues)" (Molinaro et al., 2011, pg. 20). This characterization predicts that the LAN will appear following violations where a strong syntactic prediction was made, perhaps in proportion to strength of the expectation that was violated. The importance of prediction in an *early* version of the LAN known as the ELAN has been shown in work by Lau et al., (2006; 26). In this case, a violation that occurred in a position where ellipsis was predicted as a possibility (based on the syntactic structure) found a reduction in the elicited ELAN. Put more generally, this predicts that a violation in a location where the prediction for *any* syntactic structure is weakened by the parser's prediction of possible ellipsis, will find a corresponding reduction in the amplitude of the resulting ELAN.

Phrase Structure Violations

26. a. Although Erica kissed Mary's mother, she did not kiss the daughter <u>of</u> the bride.
    b. *Although Erica kissed Mary's mother, she did not kiss Dana's <u>of</u> the bride. (LAN)

(Lau et al., 2006)

The idea that the LAN represents violations of syntactic expectation resonates with the conditions of the 'morphosyntactic LAN', given that violations are by definition less-expected than their grammatical counterparts. This account may also be compatible with cases of the LAN in response to *wh*-object dependencies, given that they are less commonly produced in spontaneous speech (Roland et al., 2007). However, in comparison with theories in which the LAN represents a necessary increase in working memory resources during the processing long-distance dependencies, the prediction approach lacks in explanatory power. Working memory accounts of the LAN are able to explain *why* object-dependencies are less-often produced, on the assumption that the additional effort they require will discourage speakers from producing them.

The LAN as a reflection of cue-based retrieval processes Recently, evidence from agreement attraction errors has supported the notion of automatic, cue-directed retrieval mechanisms (adopted from the ACT-R framework of Badecker & Lewis, 2007) in agreement processes like those which are disrupted in cases of the 'morphosyntactic LAN' (Wagers et al., 2009). According to Wagers et al., a mismatch of the features of an agreement *trigger* item (e.g., a subject) with a subsequent *target* item (e.g., a verb) can be overcome (in terms of reaction times or grammaticality judgements) in cases where an appropriately feature-matched item (e.g., a nearby RC head or PP complement NP) is present in content-addressable memory stores (McElree, 2000). It is this secondary agreement that leads speakers to treat sentences like **I think the jokes that Erin like are ridiculous* comparably to grammatical counterparts such as *I think the jokes that Erin likes are ridiculous*. In these sentences a prediction or working memory account of agreement might argue that the features of the RC head NP *the jokes* are fed-forward in a manner that either taxes working memory or increases the strength of the parser's predictions, which, if violated lead to a LAN. In contrast, Wagers et al. (2009) find little-to-no evidence of such feed-forward effects, given that delays are not found in grammatical cases where the features of an RC head NP could potentially interfere with later (grammatical) agreement relations in a subordinate clause. This sort of asymmetry would only be expected if the relevant mechanisms involved a *look-back* analysis, perhaps in response to a violation[2]. Wagers et al. describe this agreement-attraction phenomenon as a 'mistake' that occurs in cases of an ungrammaticality, however, they are also clear that their data cannot discern whether these retrieval processes are at work in *all* sentences or simply ungrammatical ones.

These cue-directed retrieval mechanisms have potential compatibility with all cases of morphosyntactic violations that elicit a LAN. Given the assumption that a local morphosyntactic discrepancy leads to a search of recent memory based on relevant linguistic cues, one can argue a plausible, if loose correlation of the 'morphosyntactic LAN' with such processes. Cue-directed retrieval mechanisms may also hold relevance for cases of the LAN in response to object-dependencies (e.g., *I know what Erin thinks is funny*). In such cases, the beginning and end of a dependency represent unlikely consecutive items (e.g., *what Erin* and *thinks is*), which may prompt some sort of search of memory for a reconciling item. If such a search was syntactically sophisticated one might expect it to occur only in the case of an actual gap (e.g., *thinks is*), where an item is posited to be retrieved or reactivated for resolution of the filler-gap relationship.

[2]see Nicol et al. (1997); Pearlmutter et al. (1999) for findings of feed-forward interference, much of which Wagers et al. (2009) attribute to bleed-over from increased reading times immediately following plurals

1.2 The P600

The P600 (Osterhout & Holcomb, 1992), also known as the Syntactic Positive Shift (SPS; Hagoort et al., 1993) is a broad posterior sustained positivity that prototypically peaks 600ms after ungrammaticalities (e.g., phrase structure and agreement violations: Neville et al., 1991, 16; Osterhout & Holcomb, 1992; Friederici et al., 1993; Hahne & Friederici, 1999, 27; Kaan, 2002; subcategorization violations: Osterhout & Holcomb, 1992, Friederici et al., 2000; island violations: McKinnon & Osterhout, 1996, 28).

1.2.1 Ungrammaticalities

Phrase Structure Violations

27. a. Das Baby wurde gefüttert.

    The baby was fed.

    b. *Die Gans wurde im gefüttert. (P600)

    The goose was in the fed.

(Hahne & Friederici, 1999)

Island Violations

28. a. I wonder whether the candidate was annoyed <u>when</u> his son was questioned by his staff member.

    *b. I wonder which of his staff members the candidate was annoyed <u>when</u> his son was questioned by. (P600)

(McKinnon & Osterhout, 1996)

1.2.2 Syntactic ambiguity and reanalysis

The P600 has also been found following misanalysis of syntactic structure (e.g., garden path sentences like Bever, 1970, 29; Osterhout & Holcomb, 1992, 30; Friederici et al., 1996; Kaan & Swaab, 2003; Osterhout et al., 1994), and during the processing of ambiguities (Frisch et al., 2002, 31).

Garden Path Sentences

29. The horse raced past the barn fell.

(Bever, 1970)

30. a. The broker hoped <u>to</u> sell the <u>stock</u>.

    b. #The broker persuaded <u>to</u> sell the <u>stock was</u> sent to jail. (P600)

(Osterhout & Holcomb, 1992)

Ambiguities

31. *First NP unambiguous/subject before object*

    a. Der Detektiv hatte die Kommissarin gesehen und...

    [the detective]$_{masc.subj}$ had [the policewoman]$_{fem.obj}$ seen and…

    First NP unambiguous/object before subject

    b. Den Detektiv hatte die Kommissarin gesehen und…

    [the detective]$_{masc.obj}$ had [the policewoman]$_{fem.subj}$ seen and…

    First NP ambiguous/subject before object

    c. Die Detektivin hatte den Kommissar gesehen und…

    [the detective]$_{fem.amb}$ had [the policeman]$_{masc.obj}$ seen and…

    First NP ambiguous/object before subject

    d. Die Detektivin hatte der Kommissar gesehen und…

    [the detective]$_{fem.amb}$ had [the policeman]$_{masc.subj}$ seen and…

(Frisch et al., 2002)

1.2.3 Dependencies

The P600 has also been found during the procession of dependencies, including object- vs. subject-dependencies (Fiebach et al., 2002, 32; Phillips et al., 2005, 33) and object-relative vs. *whether* clauses (Kaan et al., 2000, 35; Gouvea, 2003).

According to Fiebach et al. (2002), the (amplitude of the) P600 following object-dependencies does not differ based on the length of the dependency (34), which the authors interpret as evidence that the P600 reflects the *number* or *difficulty* of integrations, rather than the distance over which they occur. Work by Phillips et al. (2005) confirms these results for the P600 amplitude (33), though they do discover dependency-length effects in the P600 *latency*,which they attribute to length-sensitivities in the re-activation of the *wh*-phrase.

Object- vs. Subject-dependencies

32. a. *subj-dep*: Thomas fragt sich, wer am Dienstag den Doktor verständigt hat.

    Thomas asks himself, who_{nom} *on Tuesday* the_{acc} *doctor called has.*

    [literal translation]

    b. *obj-dep*: Thomas fragt sich, wen am Dienstag der Doktor verständigt hat. (P600)

    Thomas asks himself, who_{acc} *on Tuesday* the_{nom} *doctor called has.*

    [literal translation]

(Fiebach et al., 2002)

33. a. *short control* The detective hoped that the lieutenant knew that the shrewd witness would recognize the accomplice in the lineup.

    b. *short dependency*: The detective hoped that the lieutenant knew which accomplice the shrewd witness would recognize in the lineup. (P600)

    c. *long control* The lieutenant knew that the detective hoped that the shrewd witness would recognize the accomplice in the lineup.

    d. *long-dependency*: The lieutenant knew which accomplice the detective hoped that the shrewd witness would recognize in the lineup. (P600)

(Phillips et al., 2005)

Short- and Long-distance Object-dependencies

34. a. *short*: Thomas fragt sich, wen am Dienstag der Doktor verständigt hat. (P600) *Thomas asks himself,* who_{acc} *on Tuesday* the_{nom} *doctor called has.*

    [literal translation]

    b. *long*: Thomas fragt sich, wen am Dienstag nachmittag nach dem Unfall der Doktor verständigt hat. (P600 - same amplitude)

    Thomas asks himself, who_{acc} *on Tuesday afternoon after* the_{nom} *accident the doctor called has.* [literal translation]

(Fiebach et al., 2002)

Object-dependencies vs. Whether clauses

35. a. *whether*: Emily wondered whether the performer in the concert had imitated a pop star for the audience's amusement.

    b. *object-dep*: Emily wondered which pop star the performer in the concert had imitated for the audience's amusement. (P600)

(Kaan et al., 2000)

1.2.4 Semantically Anomalous Sentences ('Thematic P600')

Interestingly, the P600 has also been found in response to apparently *semantically* anomalous sentences (Kuperberg et al., 2003, 36; Kim & Osterhout, 2005, 37). The unique circumstances under which this P600 response is elicited have led to the name 'Thematic P600' (Stroud, 2008).

36. a. For breakfast the boys would only eat toast and jam.
    b. ?For breakfast the eggs would only eat toast and jam. (P600)

(Kuperberg et al., 2003)

37. a. The hearty meal was devoured by the kids.
    b. ?The hearty meal was devouring the kids. (P600)

(Kim & Osterhout, 2005)

1.2.5 Functional Significance of the P600: Proposals

The P600 as a reflection of syntactic integration Given its presence following various ungrammaticalities and garden path structures, the initial interpretation of the P600 was as a gauge of "syntactic reanalysis" (Osterhout & Holcomb, 1992). Recent work has maintained its functional significance as an index of "general syntactic integration difficulty" (Kaan et al., 2000; Friederici et al., 2001), based in part on evidence that the P600 is generated in response to grammatical syntactic structures that do not involve reanalysis, but which require increases in syntactic processing (which some researchers attribute to increases in *integration* costs). Work by (Friederici et al., 2002) has gone so far as to identify distinct topological representations of these two types of P600, with the repair-related positivity arising in centro-parietal areas, and with the positivity in response to more complex sentences showing a fronto-central scalp distribution.

The most noted of these more complex sentences-types are those which involve object-dependencies (Kaan, 2002; Fiebach et al., 2002; Kuperberg et al., 2003; Kim & Osterhout, 2005; Phillips et al., 2005). Such sentences are well-studied in behavioral research, with a multitude of findings indicating increased difficulty/decreased preference for object- vs. subject-dependencies.[3] In electrophysiological research, object-dependencies reliably elicit a P600 following closure of the dependency compared to (i) sentences that do not contain a dependency (e.g., sentences containing *whether* clauses), and (ii) sentences that contain a subject-dependency.

Proposals which have been put forth to account for the asymmetry of responses to subject- vs. object-dependencies according to the processing costs associated with *integration* claim that activation levels for a displaced item (e.g., *wh*-item or NP) decrease as additional material is encountered (and itself activated), which in turn leads to a greater necessary effort during reactivation and integration of the item with the appropriate verb (Gibson & Pearlmutter, 1998; Gibson, 2000). Extrapolating from this account, the P600 is not found following subject-dependencies as a result of their short duration, and the resulting *lack* of decay of the *filler*. Such length-sensitive proposals are contradicted by evidence from Phillips et al. (2005), which finds that the length of the dependency influences only the *latency* of the P600, not the amplitude. Furthermore, work by Fiebach et al. (2002) finds no length effects within object-dependencies (i.e., no difference in the P600 following a short- or long-distance dependency. As a result, Fiebach et al. (2002) claim that it is the quality or *types* of syntactic integration that matters (e.g., object-dependencies represent enough difficulty they elicit P600s).[4]

[3]This includes work showing that speakers prefer to complete *wh*-dependencies at the earliest possible integration site (Crain & Fodor, 1985; Stowe, 1986; Frazier, 1987; Frazier & d'Arcais, 1989), and that attempts to elicit object-relative clauses often lead to passive subject-relative clauses (Crain & Fodor, 1993). Furthermore, when asked to rate sentences according to complexity, (center-embedded) sentences with longer dependencies are rated significantly higher (more complex; Gibson & Pearlmutter, 1998).

[4]In behavioral data, Traxler et al. (2002) has shown that manipulations of variables other than length can reduce processing difficulty associated with object-dependencies. For example, semantic properties such as animacy can affect processing favorably (e.g., an object-relative with an inanimate head is processed more easily than one with an animate head NP).

The P600 as a reflection of dual processing streams In recent years the 'Thematic P600' (Stroud, 2008) has fueled debate as to whether its presence (and the co-occurrent, conspicuous absence of the N400) in semantically anomalous sentences is evidence for independent semantic and syntactic analyzers, with the P600 reflecting an overall mismatch in the otherwise valid outcomes of the two streams (Kim & Osterhout, 2005; van Herten et al., 2005; Kuperberg, 2007; Bornkessel-Schlesewsky & Schlesewsky, 2008). In Kim & Osterhout (2005)'s *devouring* sentences (37), an independent semantic analyzer predicts that *the hearty meal* is the object of *devour*, whereas an independent syntactic analyzer predicts it to the be the subject. When the two streams are integrated, a P600 is generated. However, work by Stroud (2008) has found that evidence of the Thematic P600 is often co-occurrent with inanimate subject nouns in an active sentences, which the authors claim represents a *syntactic* violation of the agentivity requirements verbs impose on their subjects. This account maintains the P600 as a response to syntactic phenomena, undermining the need for autonomous processing streams.

1.3 Time Frequency Analysis

While the averaging procedures of traditional ERP methods are able to isolate *evoked* (time- and phase-locked) activity that occurs in response to a stimulus (either by the addition of activity into the current signal, or by the phase-shifting of current activity to a temporarily synchronized state; Sayers et al., 1974a), any induced activity which is time-locked but not necessarily phase-locked to a stimulus (Tallon-Baudry & Bertrand, 1999a) is eliminated. Induced activity represents a part of the "noise" in an ERP that is removed by the averaging process – modulations to the ongoing, phase asynchronous oscillations occurring at the time of stimulation. These modulations reflect "changes in the activity of local interactions between main neurons and interneurons that control the frequency components of the ongoing EEG." (Pfurtscheller & da Silva, 1999). Singer (1993) argued that Gamma band oscillations could reasonably serve to establish synchronization of broadly-spatially distributed cell assemblies. Because synchronous activity increases the probability of entrainment of neurons, it is taken to facilitate activity of spatially-distant, functionally-connected networks (Bastiaansen et al., 2010). Seminal work by Gray et al. (1989b) showed that synchronous activity is crucial to binding of elements of complex representations.

> "[T]he crucial difference between evoked and induced activity is that the latter especially reflects functional changes in the parameters controlling dynamic interactions within and between brain structures" (Pfurtscheller & da Silva, 1999)

Over the last two decades, the number of applications of time-frequency methods that can isolate induced activity to classical language ERP stimuli has grown steadily (for reviews, see Weiss & Mueller, 2003; Bastiaansen & Hagoort, 2006).

1.3.1 Syntactic conditions

Focusing on findings from time-frequency analyses of strictly syntactic conditions, Bastiaansen et al. (2002) found phasic Theta power increases with distinct lateralizations for number agreement and grammatical gender violations. Weiss et al. (2005) compared object- vs. subject-relative clauses and found higher coherence in Theta and Gamma band activity during the dependency, as well as increases in coherence in Theta and lower Beta band activity (13-18Hz) just after the relative clause. Interestingly, Weiss et al. found a relative increase in lower Beta band coherence specifically between left frontal and left temporal electrodes in the object-relative clause cases. Davidson & Indefrey (2007) also found a correlation of decreased Alpha/Beta band activity in response to "grammatical" violations (which also elicited a P600). Furthermore, Bastiaansen et al. (2010) compared grammatical sentences with phrase-structure/word category violations (nouns appearing with verbal morphology), and random word sequences (asyntactic structures). Following the CW in word-category violations, Bastiaansen et al. found a decrease in Alpha and gamma power, which they attribute to the detection of violations (similar gamma suppression has been found in cases of semantic violations; Hald et al., 2006; Hagoort et al., 2004). The authors also found a variation in frontal, critical word-locked Beta band activity based on the presence and goodness of syntactic structure (correct items had greater power than category violations, which had greater power than asyntactic constructions), and a linear increase in beta activity across the entire sentence in the correct condition. This linear increase was disrupted in the violation case, and was not present in the asyntactic condition. Based on this pattern of results the authors propose that lower Beta band activity is indicative of syntactic unification – this same pattern can be more generally described as associated/reflective of syntactic structure-building. Finally, Bastiaansen et al. (2010) found linear increases in Theta band activity for correct and word category violation conditions compared with asyntactic sentences, in addition to a lack of critical word-locked variation in Theta activity across the three types (in contrast to their 2002 findings). Based on this evidence, the authors tentatively claim an association of Theta band activity and use of working memory resources, which (generally speaking) aligns with previous findings (reviewed in Bastiaansen & Hagoort, 2003; Klimesh, 1999). Given the tentativeness of the authors' current conclusions, in combination with evidence of increased Theta band power in response to semantic violations (correlated with the N400 in Hald et al., 2006; Davidson & Indefrey, 2007), it also seems logically possible that Theta activity reflects the building of a semantic representation.

Taken together, these studies create several predictions about the relevant frequencies at play in morphosyntactic violations and dependencies, including variations in Beta band activity in relation to syntactic processing and possible variations in Theta and Gamma band activity during dependencies. Interestingly, the predictions for the Beta band activity are mixed across the most common LAN-inducing conditions, including a relative decrease in Beta band power following a violation, and an increase in Beta band activity following the resolution of a dependency. Clearly, Beta band activity is of interest, however, a study with careful controls which directly compares these conditions seems warranted.

Chapter 2

The LAN: Morphosyntactic violations and dependency processing

This experiment generates *both* an event-related and time-frequency analysis of a wide-range of LAN-inducing and theoretically-related conditions, including (i) case violations, (ii) verb agreement violations, (iii) θ-criterion violations caused by "gapped" DPs, (iv) short-distance dependencies, (v) long-distance dependencies, and (vi) *+wh* sentences that include no dependencies (e.g., *I wonder whether they went to the store.*). The results of this experiment contribute intra-experimental ERP contrasts of the main LAN 'types', and also offer the unique contribution of a spectral characterization of each condition.

The over-arching goal of the experiment is to provide further evidence as to whether the LAN is truly a single electrophysiological response, or if it is a set of responses whose evoked activity shares similar characteristics. Dynamic spectral analysis of LAN-inducing conditions will provide characterizations of the frequencies comprising each LAN and the respective time-course information of those frequencies. If the the time frequency (TF) representations of the LANs generated in response to the conditions are found to involve similar frequencies as well as their similarities in topography and latency, then this will be evidence for the necessity of a joint account of the responses. This will be evidence against a purely syntactic account of the response, given the qualitative distinctions in the eliciting syntactic conditions. However, if each of the TF representations has distinct signature frequencies, this may be evidence for qualitatively different processes from topographically similar networks at play in each of the responses.

2.1 Methods

2.1.1 Participants

Thirty one men and women, including 30 students from University of California, Irvine participated in this experiment. All participants (9 male, mean age 20.67 years and 23 female, mean age 19.95 years) were healthy native speakers of English. All subjects has normal or corrected-to-normal vision and were right-handed. On average participants scored within the 6th decile of right handedness (86/100 laterality index) according to an online adaption of the Edinburgh handedness survey (Oldfield, 1971), with a median laterality of 90/100 (7th decile). All participants gave informed consent and were paid $10/hour for their participation, which lasted approximately 2.5 hours, including set-up time.

2.1.2 Stimulus Materials and Experimental Design

Our experimental materials consisted of 40 octuplets of English sentences, representing one sentence of each of our eight experimental conditions: (1) Case Control, (2) Case Violation, (3) Control, (4) θ Criterion Violation, (5) Verb Agreement Violation, (6) Whether Clause, (7) Long-distance *wh*-dependency and (8) short-distance *wh*-dependency (Table 2.1). Conditions 1-5 were designed for an analysis of left anterior negativities in response to errors in morphosyntactic processing (with conditions 6-8 serving as "filler" sentences), and conditions 6-8 were designed for an analysis of left anterior negativities in response to different types of dependencies (with conditions 1-5 serving as "filler" sentences. All of our materials were adapted from 160 sentences found in the materials of Phillips et al. (2005)[1].

Table 2.1: LAN Experiment Conditions

CC	The cameraman knew that the former mayor would honor *them* before the fireworks.
CV	The cameraman knew that the former mayor would honor *they* before the fireworks.
CONTROL	The cameraman knew *that the* former mayor would *honor the* soldiers before the fireworks.
θ VIOLATION	The cameraman knew that the former mayor would honor *before* the fireworks.
VAV	The cameraman knew that the former mayor would *honors* the soldiers before the fireworks.
WHETHER	The cameraman knew *whether the* former mayor would honor *the* soldiers before the fireworks.
WHO	The cameraman knew *who the* former mayor would honor *before* the fireworks.
WHS	The cameraman knew *who would* honor the soldiers before *the* fireworks.

All experimental sentences contained an embedded clause, whose verb phrase included a modal auxiliary verb (*would*, *could*, *should* or *might*), and a verb with a mean transitivity of 81% based on counts of the British National Corpus (im Walde, 1998). Finally, all sentences were concluded with an adjunct prepositional phrase (e.g., ... *before the fireworks.*).

Case Control sentences contained an embedded object pronoun marked with accusative case in position of the 10^{th} word. Case Violation sentences were identical to the Case Control sentences, except that the embedded object (ungrammatically) had nominative case (e.g., *they* instead of *them*). Control sentences were similar to the Case Control sentences, except that the embedded object was a full determiner phrase (e.g., *the students*). θ-criterion Violation sentences were the same as Control sentences, except that the object determiner phrase was omitted (ungrammatically). Verb Agreement Violation sentences were identical to Control sentences, except that the embedded verb in 9^{th} position appeared in the present tense, singular form (e.g., *finds*), rather than the finite tense that would be grammatical

[1] http://ling.umd.edu/~colin/research/papers/phillips_erp_wh_materials.pdf

following a modal auxiliary. Whether Condition sentences included an embedded clause headed by the complementizer *whether* instead of the complementizer *that* used in Control sentences. Long-distance *wh*-dependency sentences contained an embedded object-relative clause headed by the *wh*-complementizer *who*, and *wh*- short-distance dependency sentences contained an embedded subject-relative clause, also headed by the *wh*- complementizer *who*.

Once the sentence sets were created, eight stimulus lists were generated using a Latin square design, resulting in 40 unique tokens of each condition on each list. This ensured that no two sentences in any given list were from the same original sentence set. Following this, each of the eight stimulus lists were turned into eight unique, pseudorandomly-ordered lists, using a random number generator and manual adjustments in cases where a single condition appeared multiple times in a row.

Participants were shown the ordered lists according to their participant number, with Participants 1-8 seeing Lists 1-8, respectively, Participants 9-16 seeing Lists 1-8, respectively, and so on. In the end, Lists 1-7 were shown to four participants (e.g, List 1 was shown to P1, P9, P17, P25), and List 8 was shown to three participants (P8, P16, P24).

Table 2.2: open- and closed-class positions in a CASE CONTROL stimulus sentence

C1	O1	O2	C2	–	O3	O4	C3	O5	C4	C5	–	O6
The	professors	acknowledged	that	the	tedious	arithmetic	might	tire	us	during	the	class

Each stimulus sentence of the ordered lists was followed by a *probe word* (presented in red), half of which were *open-class*, and half of which were *closed-class*. Half of the probe words used were present in the preceding sentence (*true*), and half of them were not (*false*). Furthermore, the position the probe word either *did* come from (in the case of a *true* probe word) or *could have* come from (in the *false* probe word case) was equally distributed among the possible *open-* and *closed-class* positions for every condition (between 11 and 14 positions depending on the condition)[2]. The features *open-* or *closed-*, *true* or *false*, and *position #* were pseudorandomly assigned such that equal numbers of each were used. For cases where the probe word was *false*, a word from the corresponding position was chosen from another sentence.

2.1.3 Procedure

Before the experiment, each participant was given both verbal and written information about the EEG equipment and measurement procedures, as well as the design of the experiment and their instructions for participation. Any questions participants' had about the experiment were answered immediately. Following this, participants' completed an informed consent form, as well as an online English version of the Edinburgh Handedness Inventory.

The experiment took place in a dimly lit testing room, where participants were comfortably seated at a desk in front of a computer monitor. All experimental stimuli (other than the probe words) appeared in yellow on a blue background, in 48 pt font. Probe words were presented in red on the same blue background in the same font size. Every sentence was preceded by a fixation, which appeared in the center of the screen for 1000ms. Following the fixation, a blank screen appeared for 300ms. Sentences were presented one word at a time, with each word appearing for 300ms, followed by a blank screen for 300 ms. The one exception to this was the last word of each sentence, which appeared for 1000ms and was marked with a period. The last word was followed by a blank screen for 300ms, which was then followed by a probe word, presented for five seconds.

Participants were instructed to read sentences without blinking or moving, and to indicate

[2]For *true* probe words, there were between five and seven open- class positions (maximum: subject noun, matrix verb, adjective modifying the embedded subject, embedded subject noun, embedded verb, embedded direct object (when pronouns were not used), and embedded indirect object noun), and 4-5 closed-class positions (multiple instances of *the* were not counted). An example of the positions in a stimulus sentence is shown in Table 2.2.

with a button press whether the probe word that appeared on the screen had appeared in the preceding sentence. No feedback was provided. Prior to any stimulus materials, each participant was shown an identical list of 20 sentences that constituted a practice session, lasting approximately 4-5 minutes. The experimental session that followed was divided into 16 blocks of 20 sentences, each of which lasted approximately 4-5 minutes. Between each block, a screen appeared indicating that the participant should take a break. Participants were able to control the length of their breaks, which were ended when they pressed a button that recommenced the experiment. Each participant's session, including informed consent, equipment preparation, practice, experimental blocks and debriefing, took approximately 150 minutes.

2.1.4 EEG Recording

EEG was recorded from 32 Ag/AgCl electrodes mounted in an electrode cap (Electrocap International): (midline) FPz, Fz, Cz, Pz, POz, Oz, (lateral) FP1/2, F3/4, F7/8, FC1/2, FC5/6, C3/4, CP1/2, CP5/6 T7/8, P3/4, P7/8, O1/2, and (mastoids) M1/M2. EEG was recorded with an average reference, with no online filtering. Data was re-referenced to linked mastoids for consistency with the literature. To monitor eye movements, two additional bipolar electrodes were placed on the right and left outer canthus, and above and below the left eye. EEG and EOG recordings were amplified and sampled at 512Hz. Impedances were kept below 5 kΩ.

2.1.5 Preprocessing

Data analysis was performed using the EEGLAB (Delorme & Makeig, 2004, `http://sccn.ucsd.edu/eeglab/`)), ERPLAB (Lopez-Calderon & Luck, 2014, `http://erpinfo.org/erplab`)), and Fieldtrip (Oostenveld et al., 2011, `http://www.fieldtriptoolbox.org/`)) software packages, all of which are Matlab toolboxes used for the analysis of EEG and MEG data.

For both the amplitude and time-frequency analyses, trials containing ocular, muscle or other large artifacts were identified and removed based on visual inspection (6.7% total). The number of excluded trials was not significantly different between conditions ($F_{16,16303} = 1.32, p = 0.17$), resulting in an average of 37 trials per condition for each subject.

2.1.6 Event-related Potential Analysis

For the ERP analysis, stimulus sentences were first segmented from the larger EEG using boundary markers, and channels were re-referenced to the average of the two mastoid channels. The resulting sentence segments were high-pass filtered at 0.1Hz using a second-order butter worth filter, and DC bias was removed. Event epochs were then segmented 200ms before to 1000ms after each critical word, and the resulting epochs were low-pass filtered at 30Hz with a second-order butterworth filter. Trials containing artifacts were removed, and the remaining trials were grand averaged at each channel.

Statistical comparisons of the resulting condition grand average ERPs were made using the Mass Univariate ERP Toolbox (Groppe et al., 2011, `http://openwetware.org/wiki/Mass_Univariate_ERP_Toolbox`). The *mass univariate analysis* (Woolrich et al., 2009) approach is an answer to the coarse nature of more typical ERP analyses, which compare average activity across swaths of electrodes and time points. The t_{max} and *cluster-based* approaches in particular were chosen, based on recent work showing their robustness in cases where data is highly correlated (Hemmelmann et al., 2004).

t_{max} *permutation tests*

The ERP difference waves for each pair of the conditions were analyzed with a repeated-measures two-tailed permutation test based on the t_{max} statistic (Blair & Karniski, 1993), with a family-wise error rate of α=0.05. Activity from each of the 30 non-reference channels (mastoids excluded) were compared in two time windows of interest, which were selected as windows in which the LAN (200-500ms, 9216 comparisons) and P600 (400-900ms, 15360 comparisons) were commonly identified in previous research.

In this permutation, a t-test was performed for each channel$\times$time point, using the original data and data from 2500 random, within-subject permutations of each subject's data (2500 permutations is suggested by the literature as it is more than twice the number recommend by Manly (2006) to achieve a family-wise α of 0.05). From each of the tests, the most extreme t-score was selected and a distribution of these "t_{max}" scores was estimated. The t_{max} score from the original data was then compared against this estimated distribution, as a non-parametric approach to the statistical comparison (Maris, 2004). Based on these estimates, a critical t-score was established, and any data exceeding that value was marked as significant.

cluster-based permutation tests

In addition to permutation tests based on the t_{max} statistic, a series of repeated measures, two-tailed *cluster-based* permutation tests were also performed for the time windows of interest (200-500ms and 400-900ms), using the cluster mass statistic (Bullmore et al., 1999) and a family-wise α level of 0.05. Cluster permutation tests were computed in a manner fairly similar to the t_{max} approach, with repeated-measures $t-$tests performed on the original data and 2500 random permutations of the data, however in this case t-scores less than a threshold α (here 0.05) were selected at each permutation and summed in *clusters*. The most extreme resulting cluster sum or "mass" at each permutation was then used to estimate the null distribution. With this, the permutation cluster mass percentile ranking of each cluster in the actual data was used to calculate a corresponding $p-$value, and that $p-$value was then assigned to all channels in the cluster.

Following this, a second round of cluster-based tests were performed using a more relaxed α threshold of 0.08, and a similarly relaxed FWER (α=0.08).

Clusters were determined based on spatial and temporal features, with electrodes within 5.77 cm of each other considered spatial neighbors and adjacent time points considered temporal neighbors. Given these parameters, the median number of channels per cluster was 4, with a minimum of 2 channels and a maximum of 6 in a cluster.

An advantage of the cluster-based approach is that it captures the broader regional effects (activity extending across several electrodes) often seen in ERPs (e.g., the P300), and is thought to be the most powerful mass univariate procedure to detecting broadly distributed effects (Groppe et al., 2011; Maris & Oostenveld, 2007)

2.1.7 Time-Frequency Analysis

Time-frequency representations of the activity surrounding the critical word of each condition were created using the software package Fieldtrip (Oostenveld et al., 2011), on event epochs -500ms to 1000ms after the onset of the critical word. In a fashion somewhat similar to the preprocessing steps of the ERP analysis, epochs were extracted from the data, were baselined according to the average activity prior to the critical word onset, were detrended to remove any large, non-meaningful drifts in the data, and were rereferenced to the average of the two mastoid channels. Frequency activity within the window was then estimated in steps of 20ms, using a multitapered Fourier analysis approach with 'sliding' (and overlapping) Hanning windows.

In this type of analysis, a window containing a pure sine wave of a given frequency is convolved with the data for an estimate of the average activity at that frequency within the duration of the window. Windows of 5 cycles (5 wavelengths) were used to estimate activity in each frequency between 2 and 50 Hz, in 1 Hz steps. The length of the window was determined by the frequency being measured, which optimized the time×frequency trade-off in precision. With this approach, smaller windows could be used to estimate higher frequencies, increasing the temporal precision of the estimate. Furthermore, frequency window edges were smoothed in order to avoid edge effects in the estimates, by multiplying the frequency wave with an inverted cosine (the properties of which were a function of frequency as well). The result of this is a Hanning (Hann) window. Because tapering in the Hanning window necessarily means the loss of data at either edge of the window in each estimate, the estimates made using the window were overlapping (the window was successively 'slid' to the right, to an extent determined by the number of time points estimated for each frequency - here in steps of 20ms). This type of analysis has been used in similar existing work examining the brain's response to sentence processing (Bastiaansen & Hagoort, 2006, e.g.).

In this TF analysis, the baseline window was extended from the -200ms used in a typical ERP analysis to -500ms, to accommodate a minimum 2Hz frequency resolution of the baseline window. Furthermore, given that the smallest frequency activity examined statistically was 4Hz, this baseline window allowed for at least two wavelengths of each frequency in the baseline window (a standard preferred for our analysis).

Finally, the resulting TFRs were averaged for each subject to create a representation of changes in induced frequency activity for each subject (Tallon-Baudry & Bertrand, 1999b). Subsequently, a statistical comparison of each condition was computed using the monte-carlo estimate of non-parametric significance probabilities (using permutation methods similar to those in the ERP analysis). In this case, in each statistical comparison the labels for each condition for each subject were randomly shuffled between conditions/subjects a large number of times, and each time a two-tailed dependent sample t-statistic and corresponding p-value were calculated, estimating the probability distribution for the null hypothesis.

The number of permutations used was determined as a function of the critical α value (here, 0.01), which was divided by the inverse of the number of comparisons (the number of channels×frequencies×time points) for each of five frequency bands. This number was multiplied by 1000, resulting in a number of permutations between 10,000 and 20,000.

2.2 Results

2.2.1 Accuracy

Among the 30 participants included in the analysis, accuracy in the target-monitoring task was measured as a difference in accuracy and bias. The average d' for participants was 2.52, indicating a high signal detection.

2.2.2 ERPs and TFRs

Case Violation

CC The cameraman knew that the former mayor would honor *them* before the fireworks.
CV The cameraman knew that the former mayor would honor *they* before the fireworks.

ERPs

In a comparison of the Case Violation condition with the Case Control condition, there is a visible negative going deflection at 400ms and 500ms, which corresponds to a statistically significant cluster of negative activity between 300-500ms, in mostly left hemisphere channels (Fig. 2.4), as well as (more limited) significant negative activity in left frontal and left posterior channels between ∼390-420ms, according to the t_{max} permutation results (Fig. 2.3). In later time windows the t_{max} permutation tests also reveal significant positive activity between ∼700-775ms, in right posterior channels.

Figure 2.1: Case Violation: ERPs

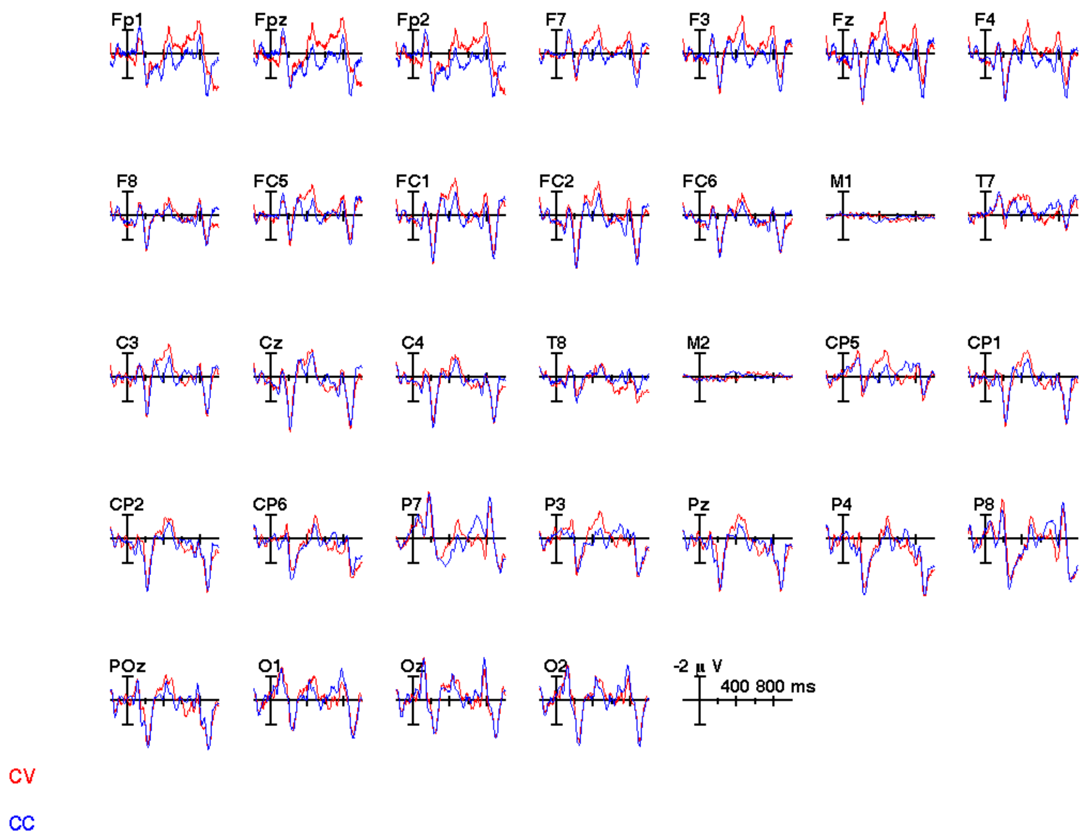
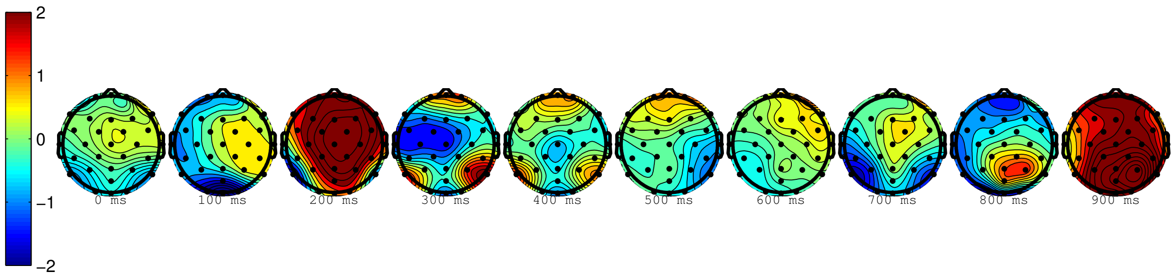
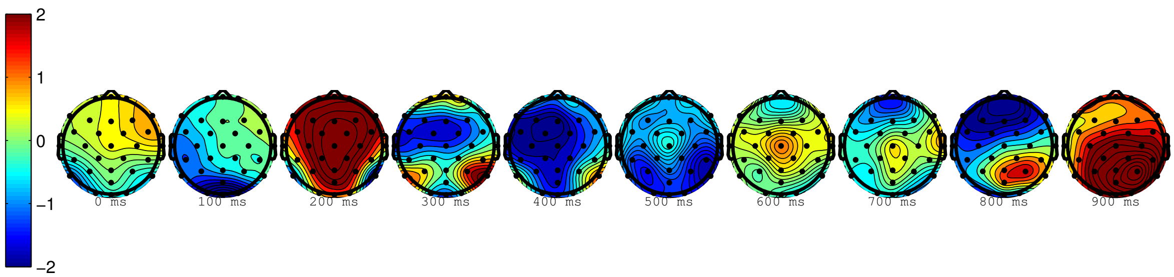


Figure 2.2: Case Violation: topoplots

Case Control



Case Violation



Difference plots

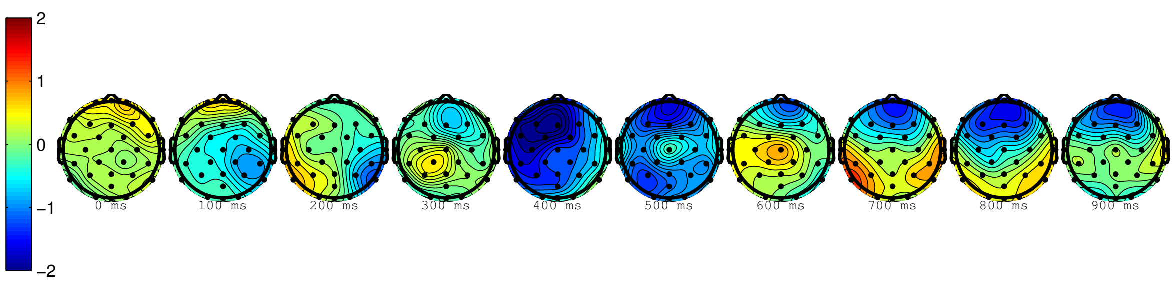


Figure 2.3: Case Violation: t_{max} permutation tests

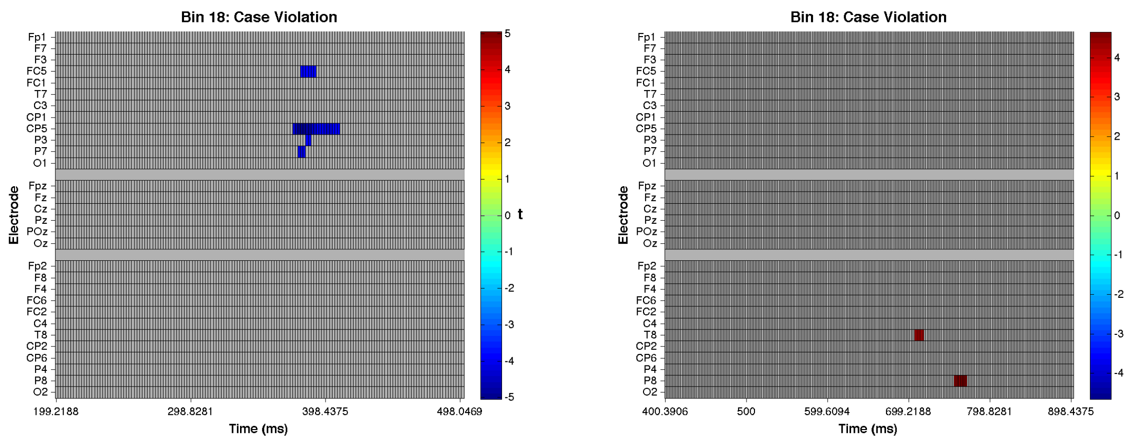
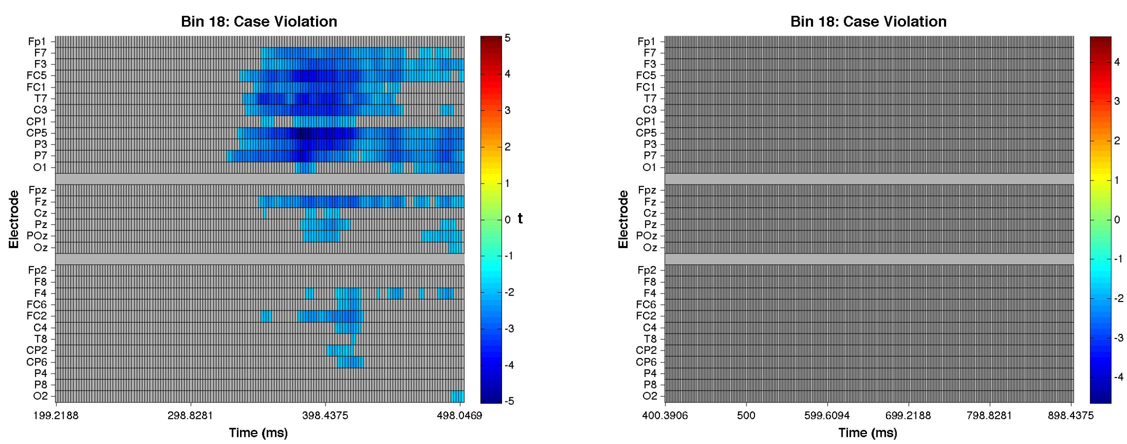


Figure 2.4: Case Violation: cluster mass permutation tests



TFRs

Comparing the Case Violation and Case Control conditions, there is a significant bilateral parietal decrease in 7Hz activity at ∼550ms, a broad anterior decrease in 9-12Hz activity from ∼550-800ms and in 13-16Hz activity from ∼600-725ms, followed by a left parietal decrease in 10-13Hz areas at ∼725ms.

Overall, in the Case Violation condition, Theta activity (7Hz) decreases in parietal areas bilaterally at ∼550ms. Alpha band activity decreases in anterior areas broadly from ∼550-800ms and in left parietal areas at ∼725ms. Lower Beta activity decreases in broad anterior areas from ∼600-725ms, and no significant differences in either Upper Beta or Gamma band activity were found.

Figure 2.5: Case Violation: TFR

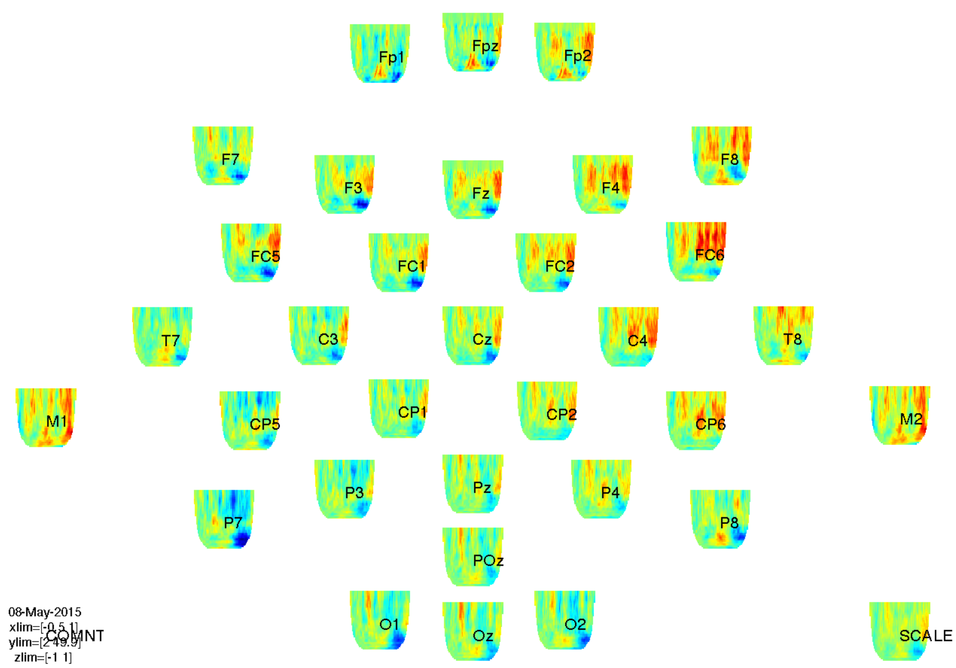


Figure 2.6: Case Violation: Theta band (4-7Hz) masked stats TFR

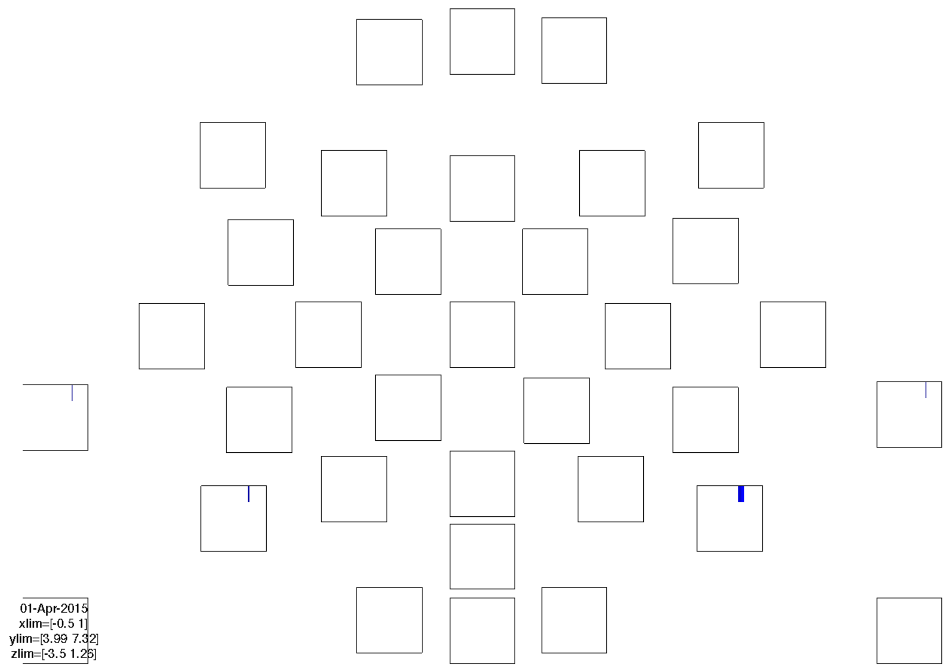


Figure 2.7: Case Violation Condition: Theta band (4-7Hz) masked stats TFR, significant channels

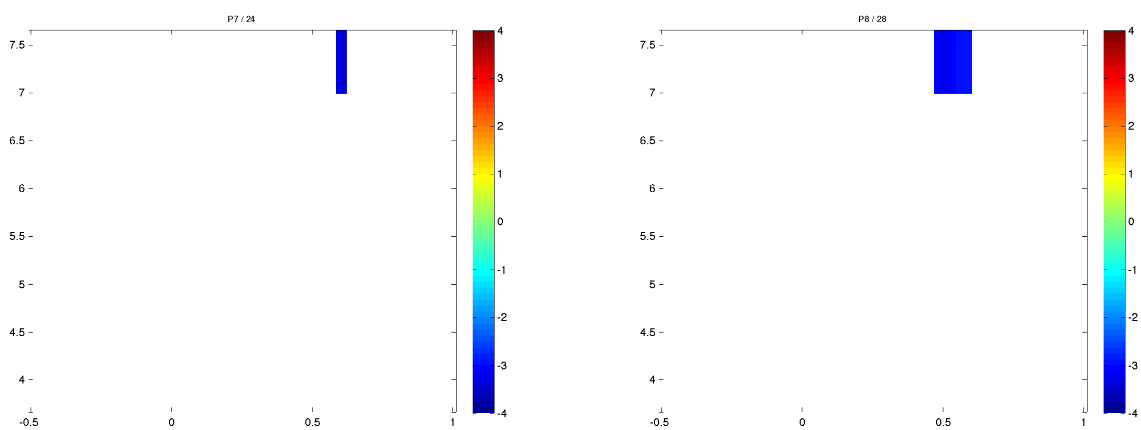


Figure 2.8: Case Violation: Alpha band (8-12Hz) masked stats TFR

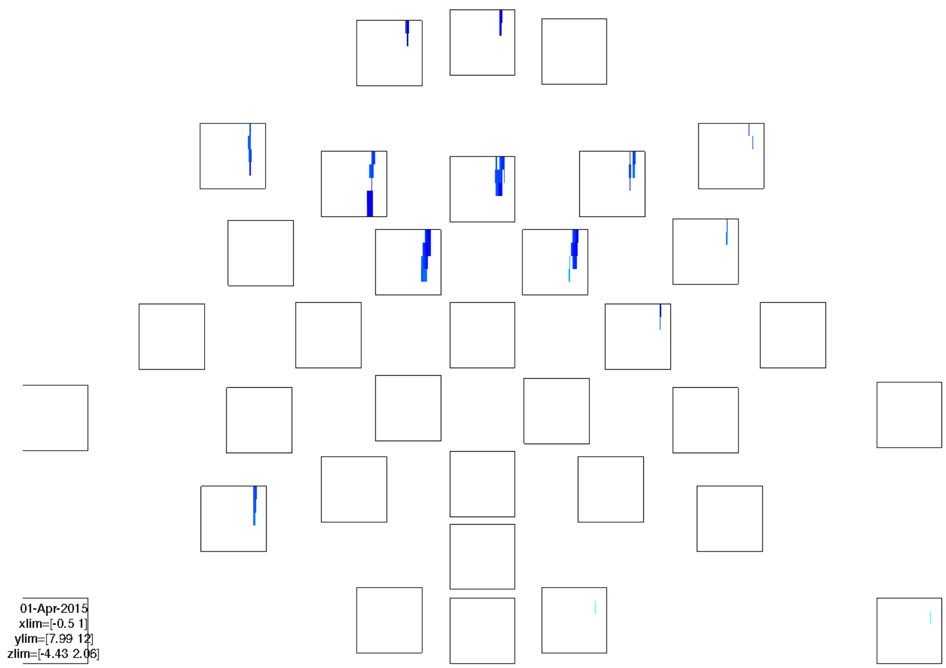


Figure 2.9: Case Violation Condition: Alpha band (8-12Hz) masked stats TFR, significant channels

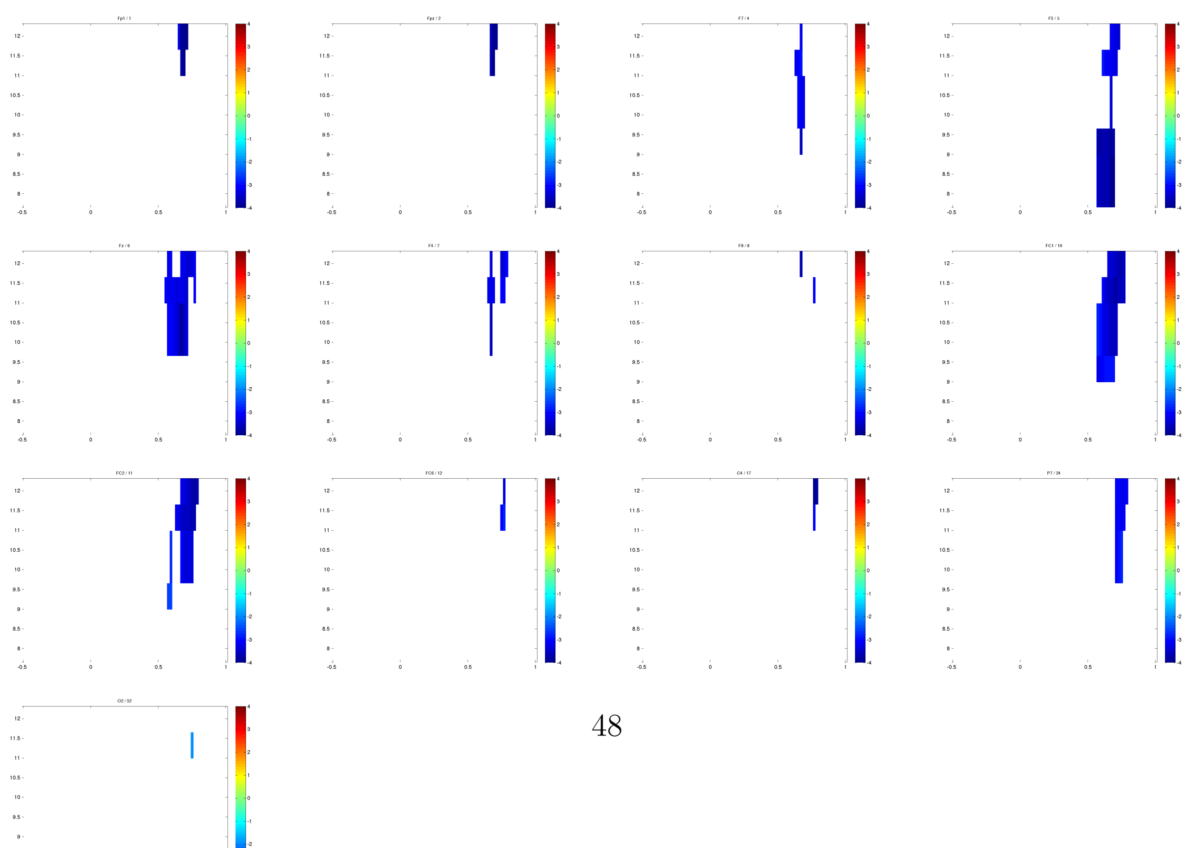


Figure 2.10: Case Violation: Lower Beta band (13-20Hz) masked stats TFR

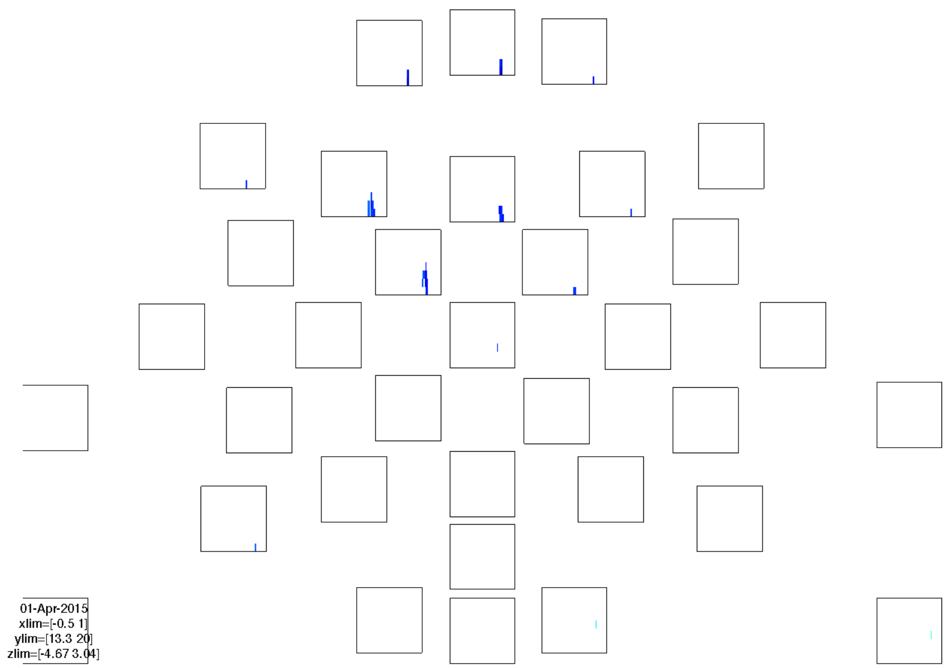
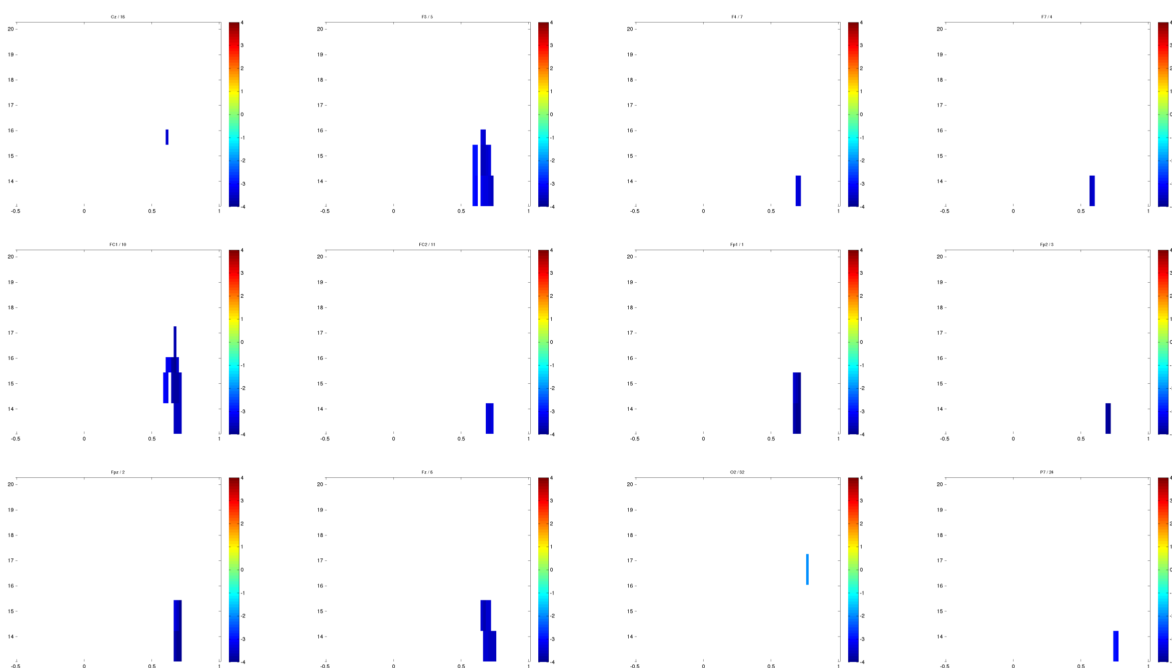


Figure 2.11: Case Violation Condition: Lower Beta band (13-20Hz) masked stats TFR, significant channels



Verb Agreement Violation Condition

CONTROL	The cameraman knew *that* *the* former mayor would *honor* *the* soldiers before the fireworks.
VAV	The cameraman knew that the former mayor would *honors* the soldiers before the fireworks.

ERPs

In a comparison of the Verb Agreement Violation condition with the Verb Control condition, there is a visible positive deflection in early (100-300) and late time windows (600-900ms) following the violation condition. This positivity is significant in left posterior channels between ~775-900ms according to the t_{max} permutation tests (Fig. 2.14), and is found to represent broad clusters of significant positive activity in bilateral (slightly more posterior) areas, according to the cluster permutation tests (Fig. 2.15).

Figure 2.12: Verb Agreement Violation: ERPs

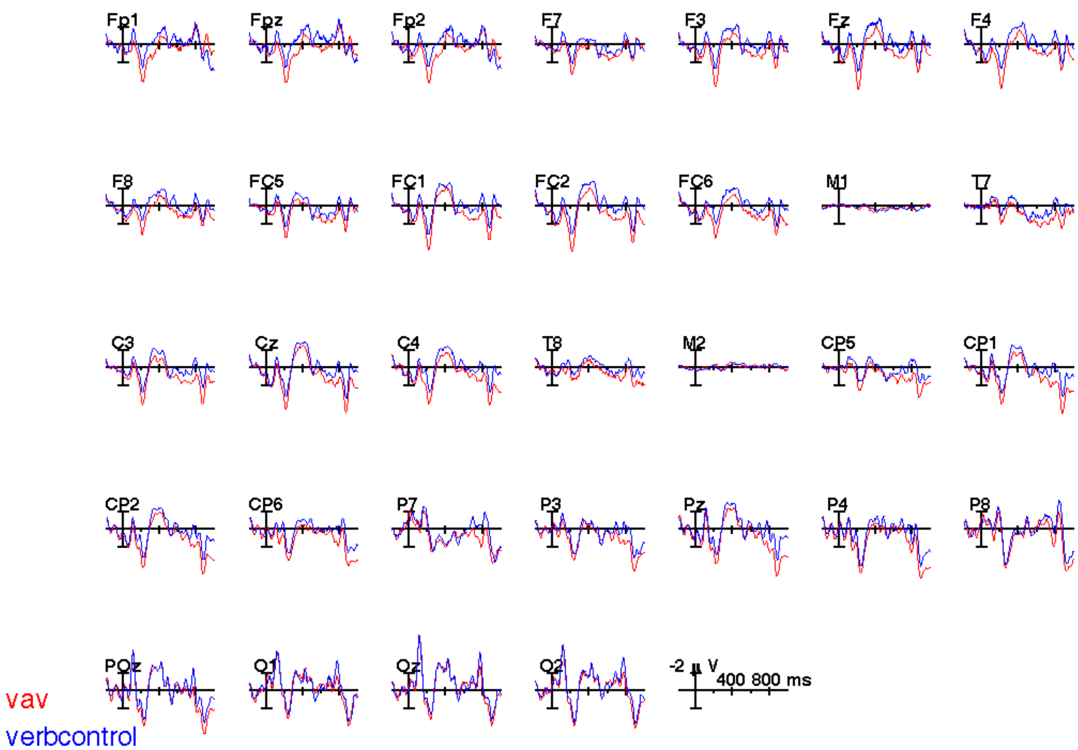
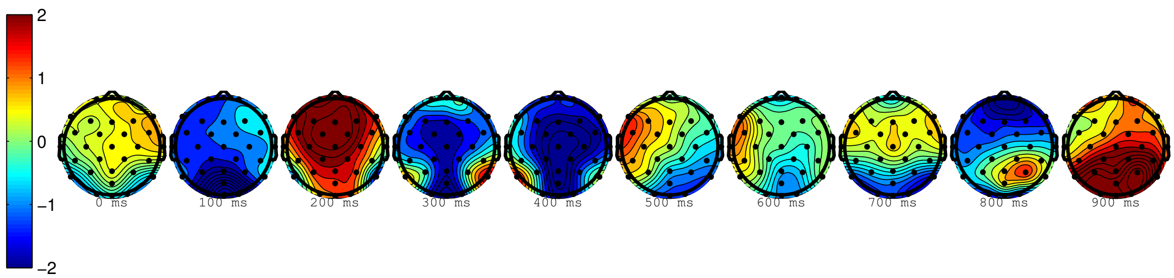
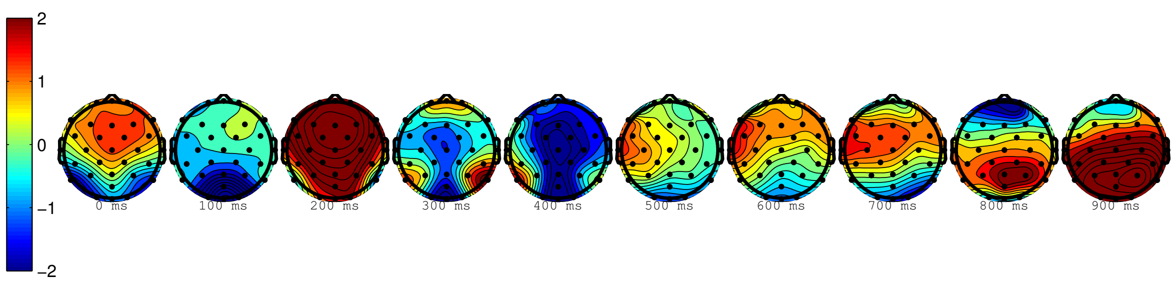


Figure 2.13: Verb Agreement Violation: topoplots

Verb Control



Verb Agreement Violation



Difference plots

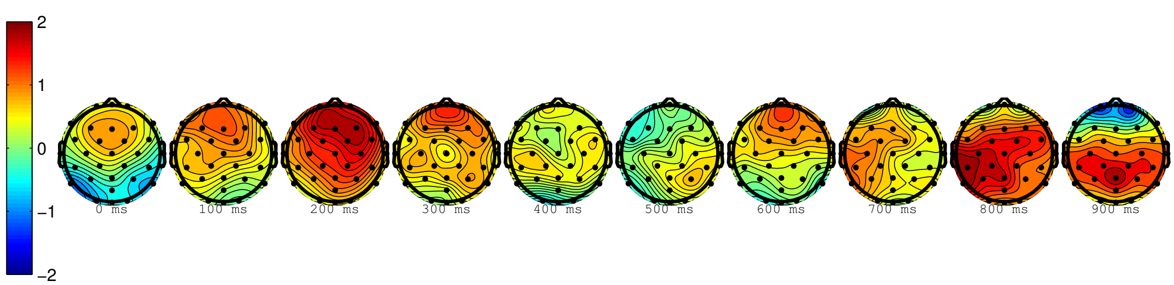


Figure 2.14: Verb Agreement Violation: t_{max} permutation tests

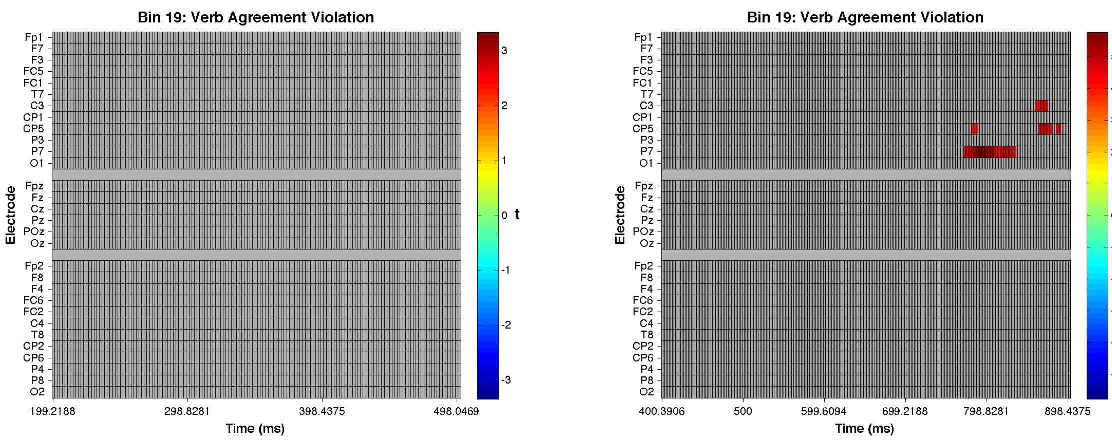
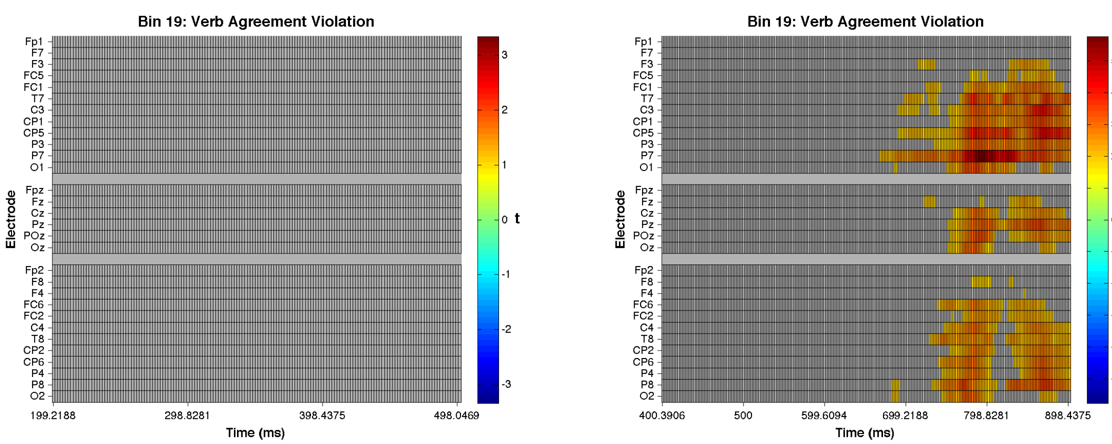


Figure 2.15: Verb Agreement Violation: cluster mass permutation tests



TFRs

Comparing the Verb Agreement Violation and Verb Control conditions, there is a significant increase in 5-6Hz activity in occipital areas at the point of onset of the critical word (e.g., ... *they would* honors *the soldiers* .... This is followed by a significant increase in 11-12Hz activity in left anterior areas at ∼300ms post-cw, a prefrontal increase in 20Hz activity at ∼450ms, a right parietal decrease in 7-11Hz at ∼500ms, a broad anterior decrease in 9-14Hz activity from ∼600ms to ∼800ms, and a left parietal decrease in 14-17Hz activity at ∼600ms.

Overall, in the Verb Agreement Violation condition, Theta band activity increases in occipital areas at critical word onset, and decreases (7Hz) in right parietal areas at ∼550ms. Alpha band activity increases in left anterior areas at ∼300ms post-cw and then decreases in right parietal areas at ∼500ms and in broad anterior areas from ∼600-800ms. Middle Beta activity (20Hz) increases in prefrontal areas at ∼450ms, and Lower Beta activity decreases between ∼600-800ms in broad anterior areas, and in left parietal areas.

Figure 2.16: Verb Agreement Violation: TFR

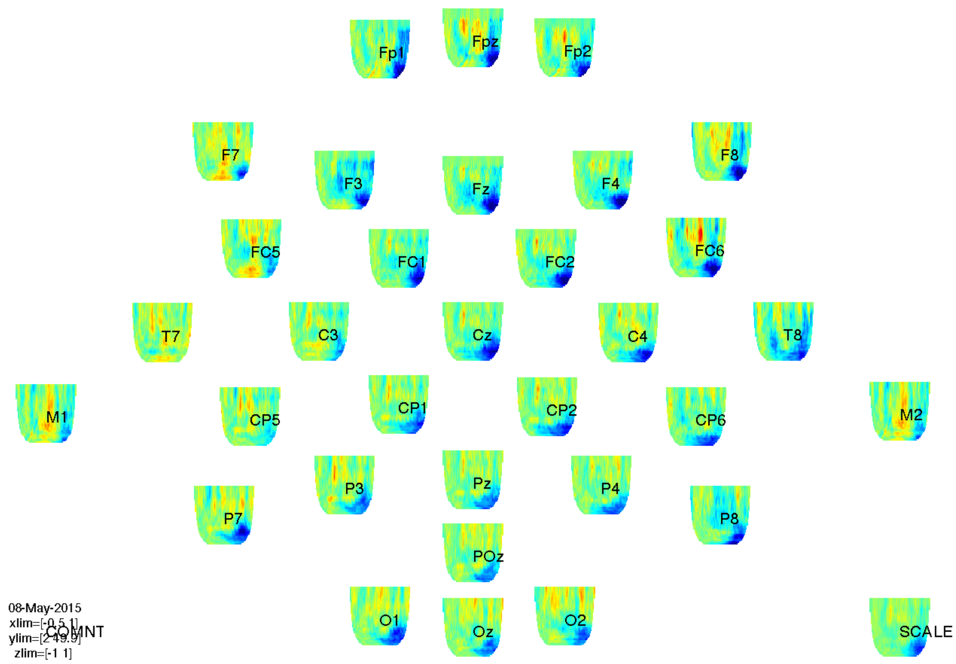


Figure 2.17: Verb Agreement Violation: Theta band (4-7Hz) masked stats TFR

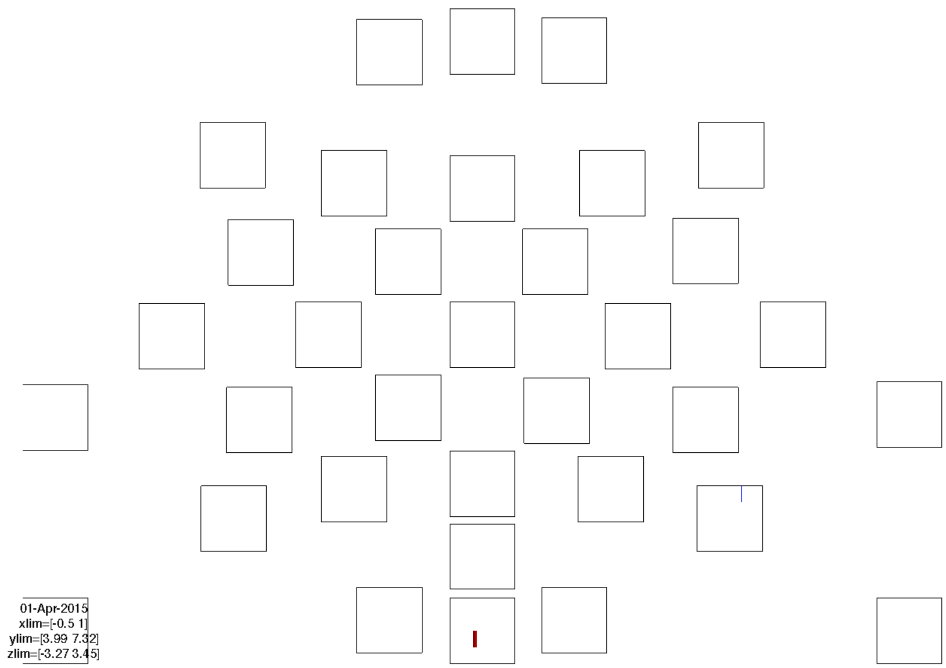


Figure 2.18: Verb Agreement Violation: Theta band (4-7Hz) masked stats TFR, significant channels

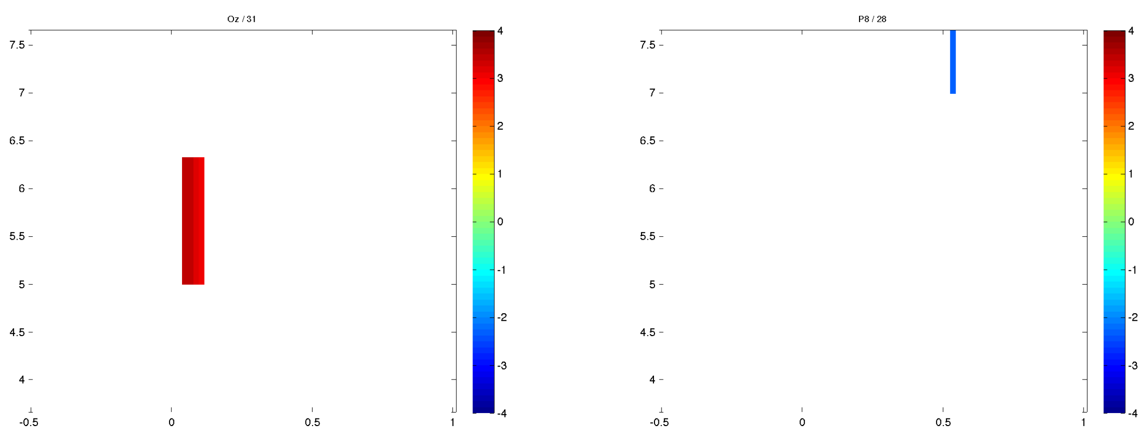


Figure 2.19: Verb Agreement Violation: Alpha band (8-12Hz) masked stats TFR

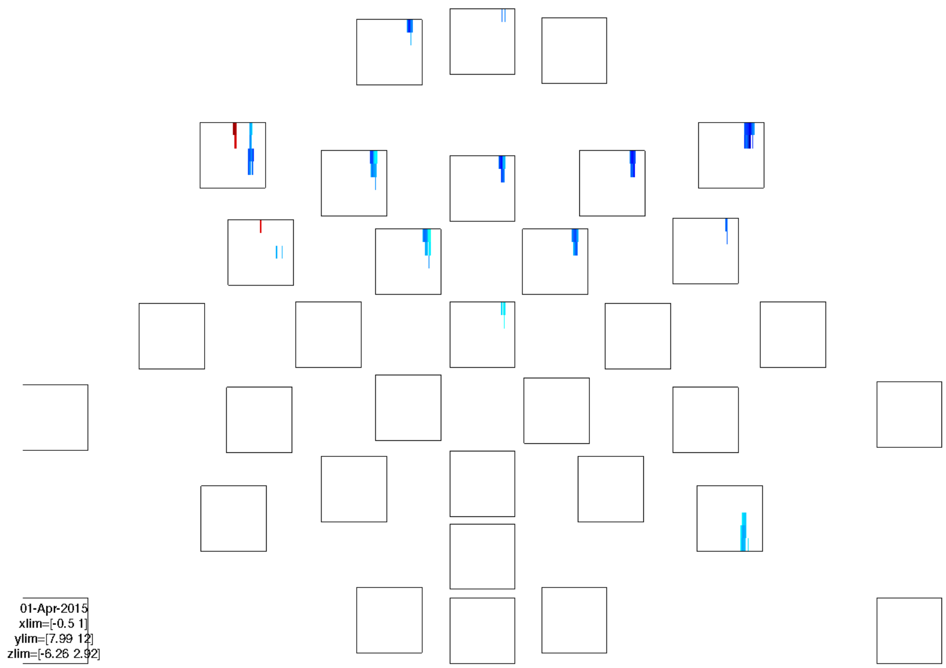


Figure 2.20: Verb Agreement: Alpha band (8-12Hz) masked stats TFR, significant channels

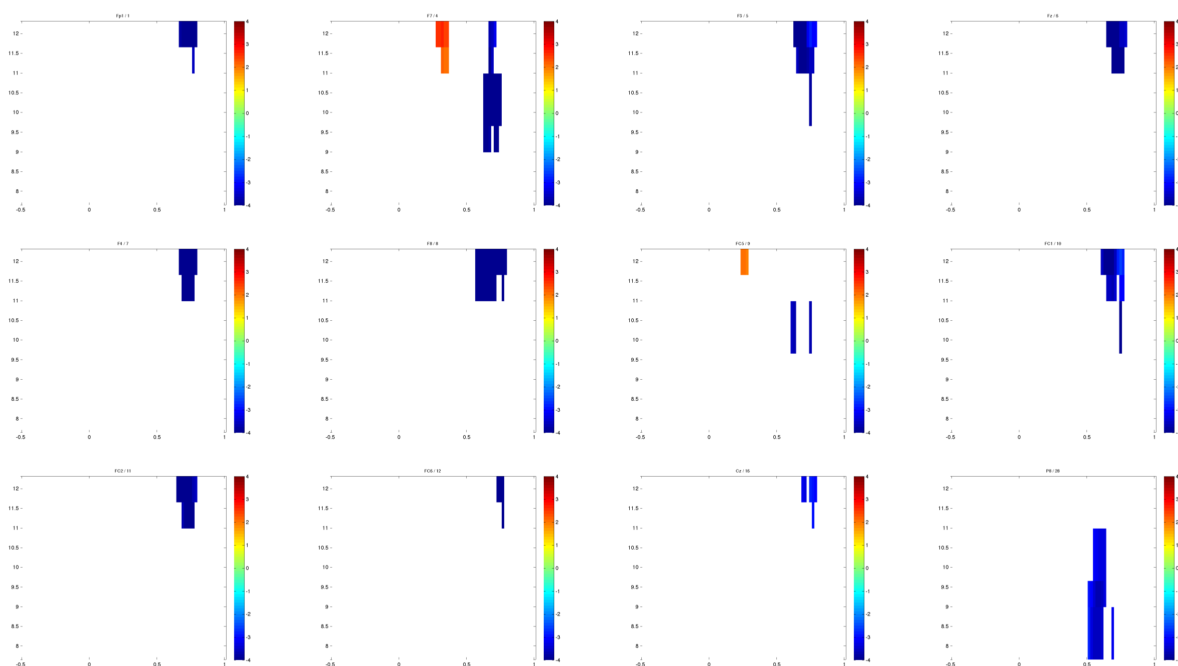


Figure 2.21: Verb Agreement Violation: Lower Beta band (13-20Hz) masked stats TFR

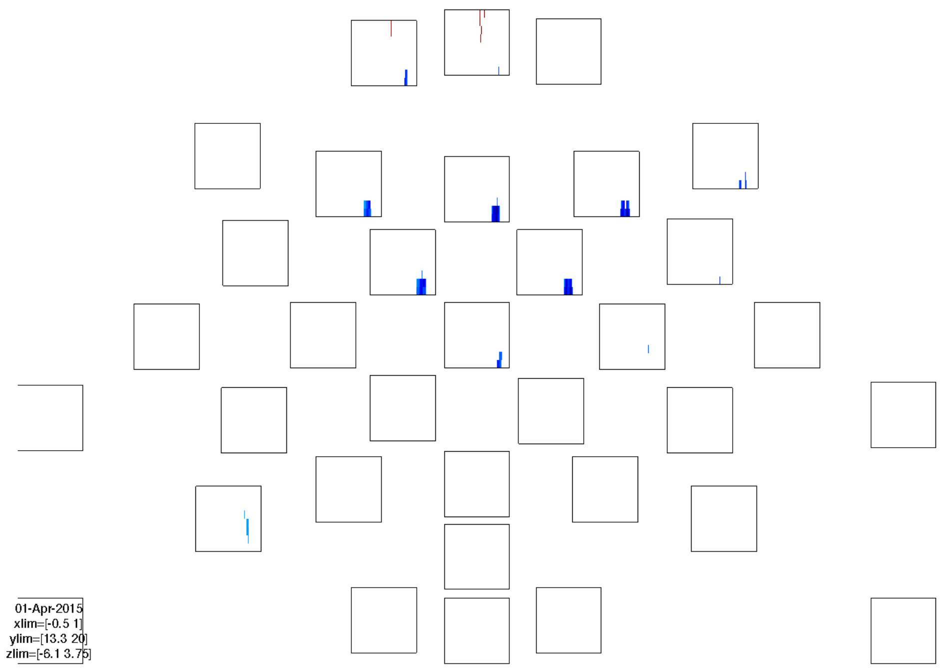
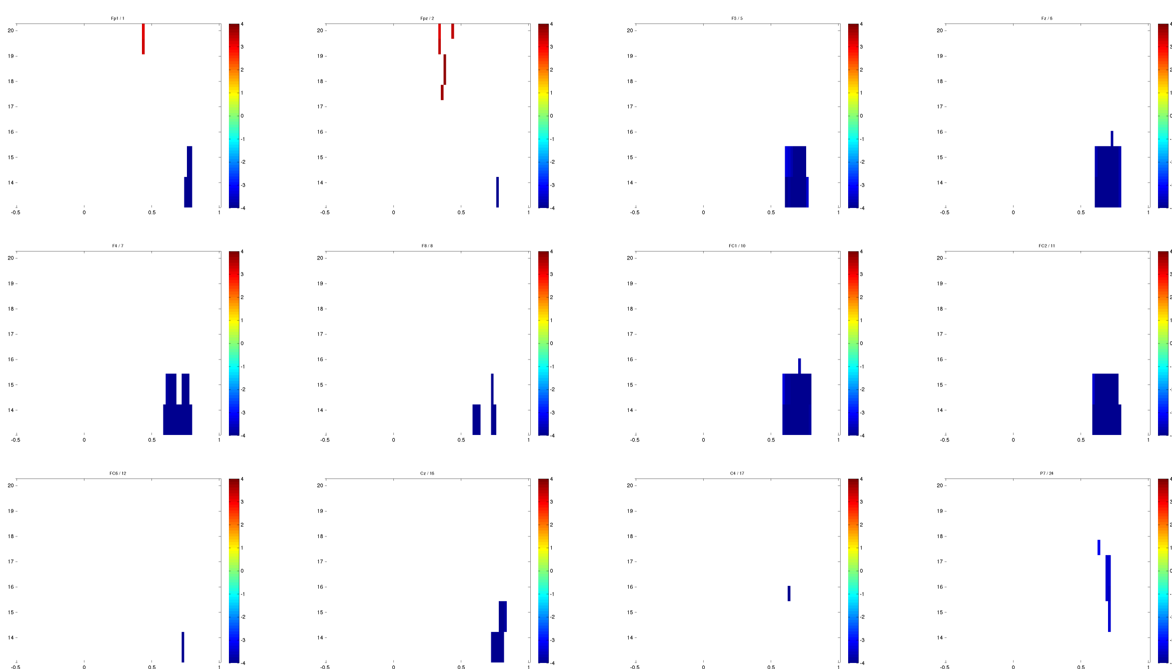


Figure 2.22: Verb Agreement Violation: Lower Beta band (13-20Hz) masked stats TFR, significant channels



θ-Criterion Violation

CONTROL	The cameraman knew *that* *the* former mayor would *honor* *the* soldiers before the fireworks.
θ-VIOLATION	The cameraman knew that the former mayor would honor *before* the fireworks.

ERPs

In a comparison of the θ-Criterion Violation condition with the DO of the Control condition, there is an early right posterior negativity at ∼300ms, and a positive going deflection that is visible in 100ms time slices from 400-800ms. The results of the t_{max} permutation tests reveal significant negativities in middle and right occipital channels at ∼300 and ∼500ms, as well as significant positive activity in (primarily) left hemisphere channels broadly from ∼400 and ∼800ms (Fig. 2.25). Cluster-based analyses reveal large (primarily left-hemisphere) clusters of positive activity from ∼400 and ∼800ms as well (Fig. 2.26), beginning in left anterior and temporal areas and moving to more posterior areas.

Figure 2.23: θ-Criterion Violation: ERPs

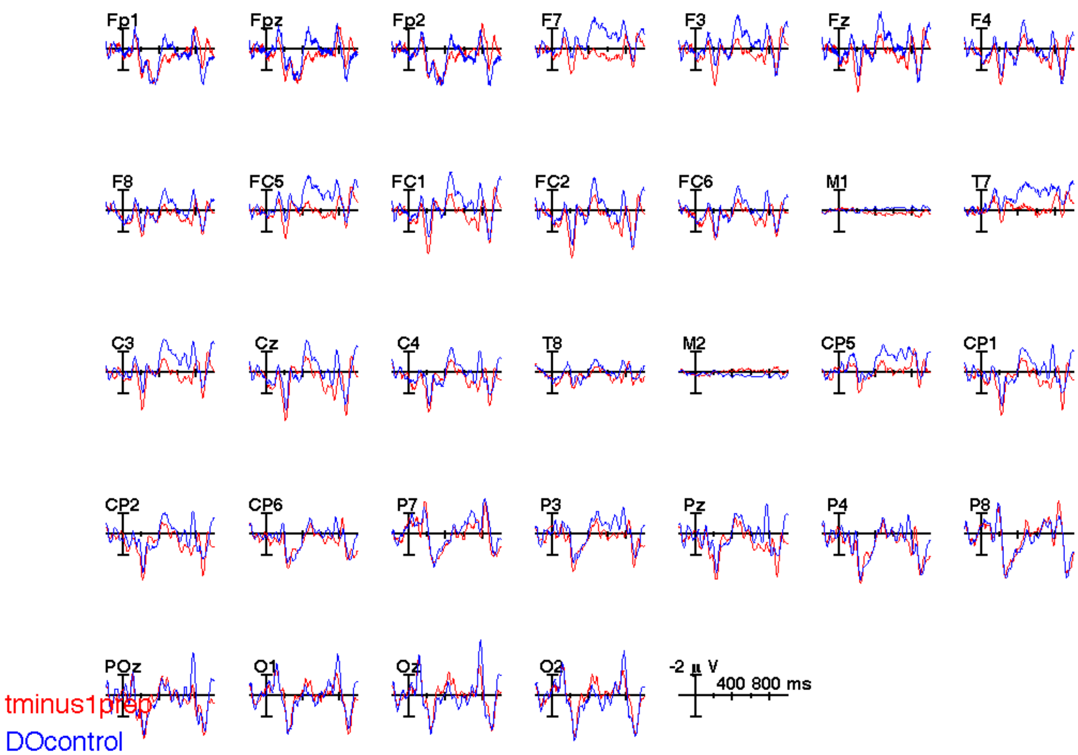
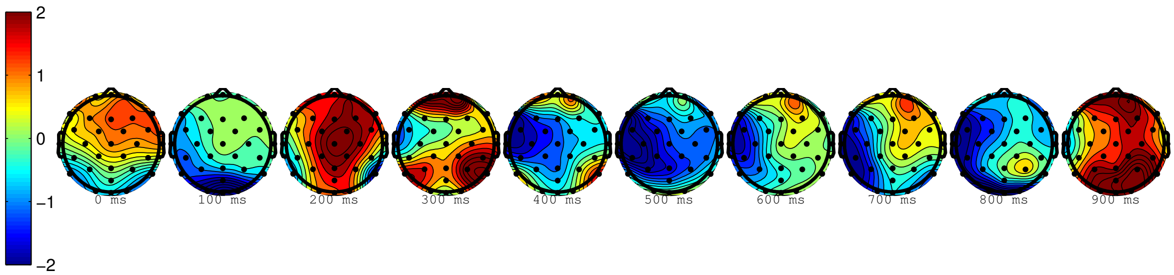
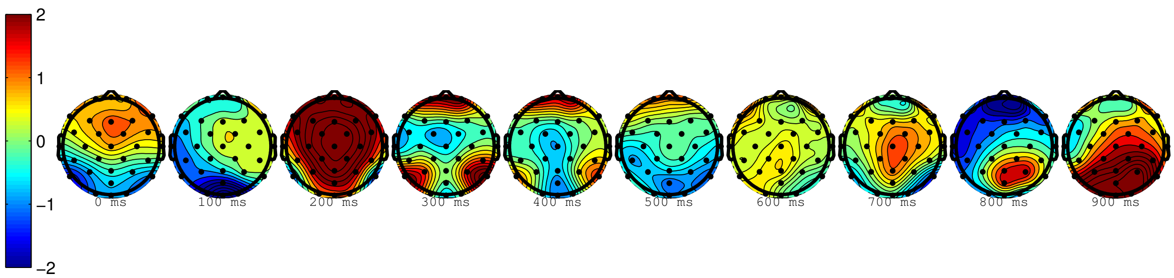


Figure 2.24: θ-Criterion Violation: topoplots

DO Control



θ-Criterion Violation



Difference plots

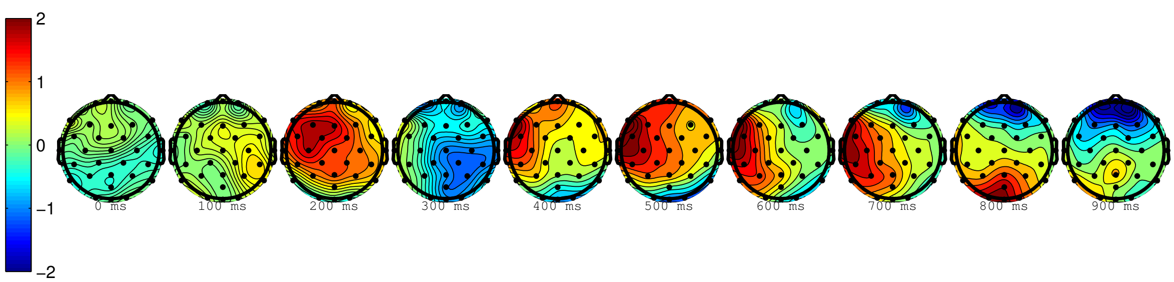


Figure 2.25: θ-Criterion Violation: t_{max} permutation tests

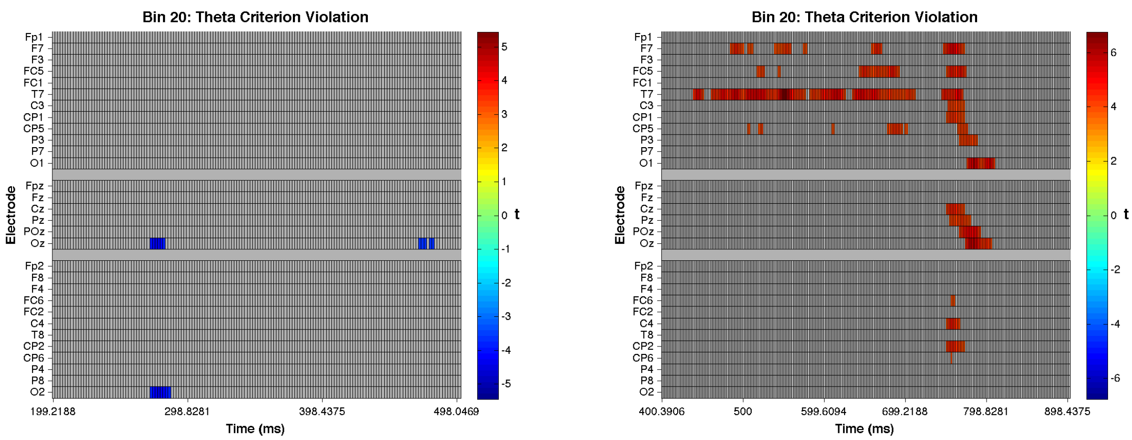
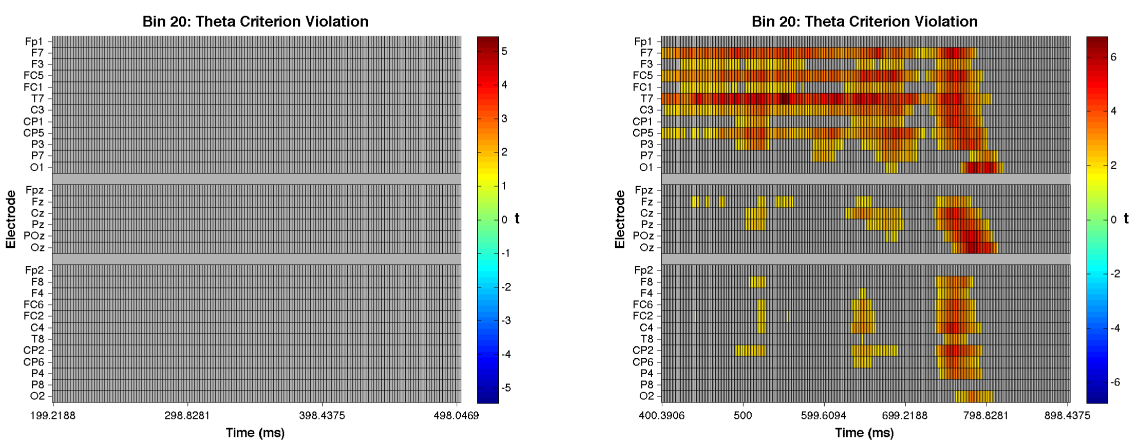


Figure 2.26: θ-Criterion Violation: cluster mass permutation tests



TFRs

Comparing the θ-Criterion Violation and θ-Criterion Control conditions, there is a significant decrease in 26-27Hz activity in prefrontal areas at ∼50ms, an increase in the range of 34-40Hz in right parietal areas at ∼350ms, a decrease in 17Hz in occipital areas at ∼450ms, a decrease in 8-15Hz in left centro-parietal areas at ∼500ms, a decrease in 7Hz in left centro-parietal areas at ∼575ms, a decrease in 7Hz in right anterior areas at ∼575ms, a decrease in 6Hz in occipital areas at ∼575ms, a decrease in 8, 11 and 12Hz in right temporal areas at ∼625ms, and an increase in 23Hz in left occipital areas at ∼900ms.

Overall, in the θ-Criterion Violation condition, Theta band activity decreases in left centro-parietal, right anterior, and occipital areas at ∼575ms. Alpha band activity decreases in left centro-parietal areas at ∼500ms and right temporal areas in 8, 11, and 12Hz at ∼625ms. Lower Beta activity decreases in occipital areas at∼450ms, and in left centro-parietal areas at ∼500ms. Upper Beta activity decreases in prefrontal areas at ∼50ms, and increases in left occipital areas at ∼900ms. Finally, Gamma activity increases in right parietal areas at ∼350ms.

Figure 2.27: θ-Criterion Violation: TFR

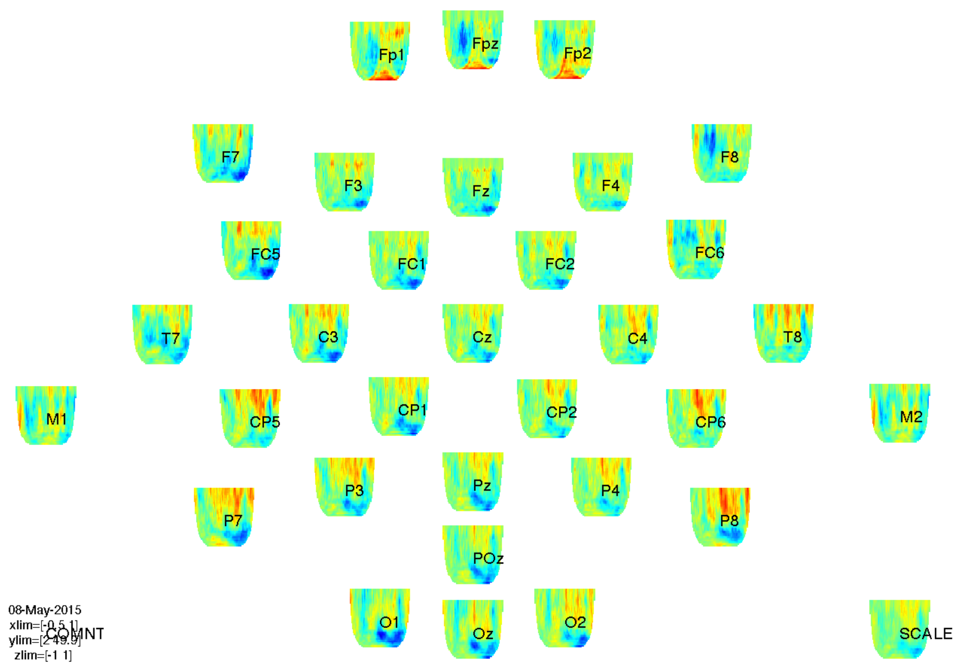


Figure 2.28: θ-Criterion Violation: Theta band (4-7Hz) masked stats TFR

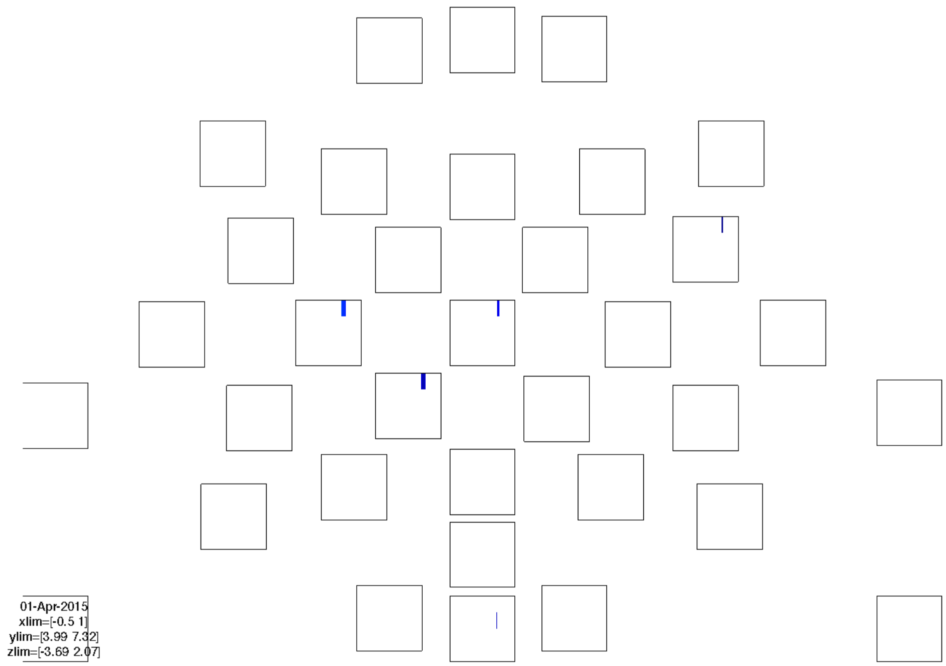


Figure 2.29: θ-Criterion Violation: Theta band (4-7Hz) masked stats TFR, significant channels

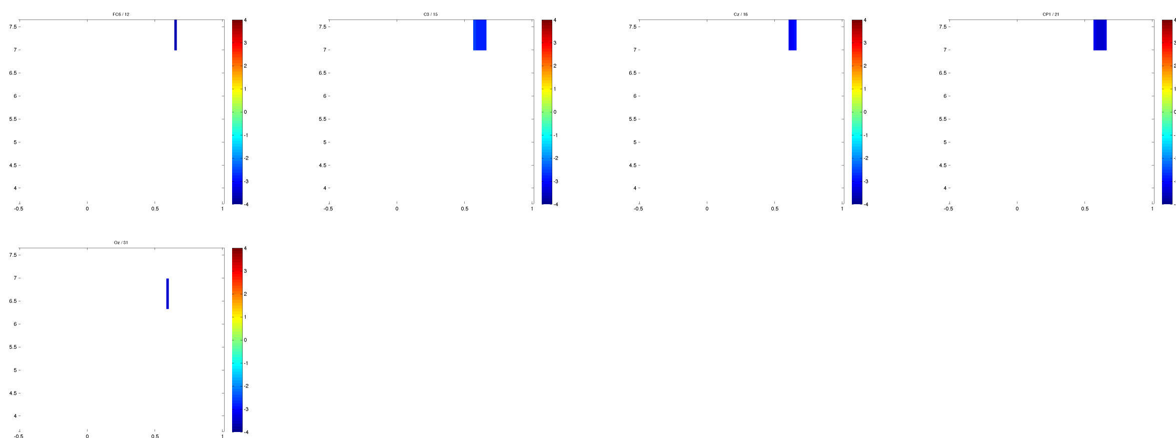


Figure 2.30: θ-Criterion Violation: Alpha band (8-12Hz) masked stats TFR

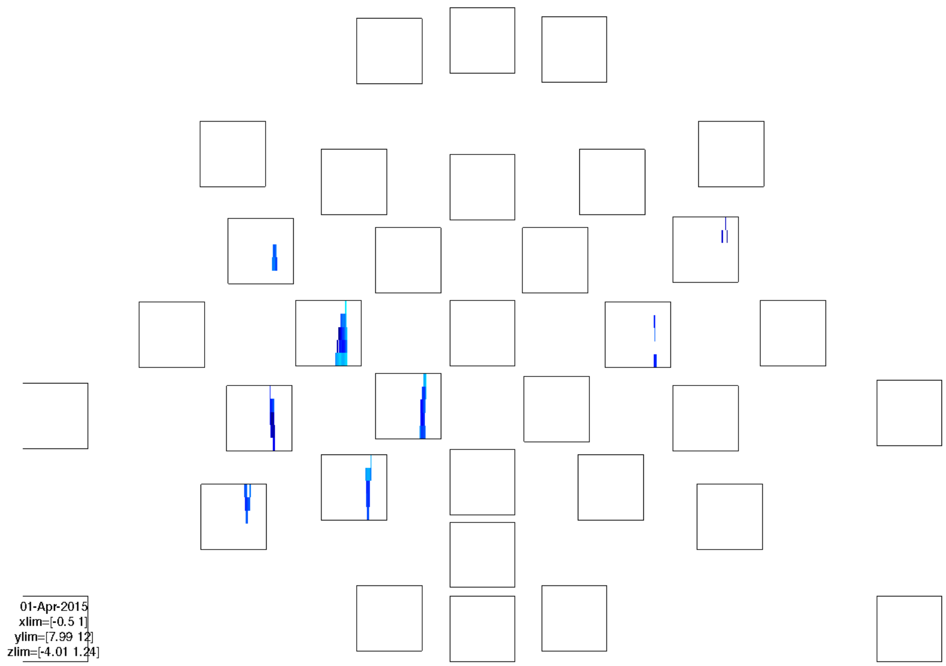


Figure 2.31: θ-Criterion: Alpha band (8-12Hz) masked stats TFR, significant channels

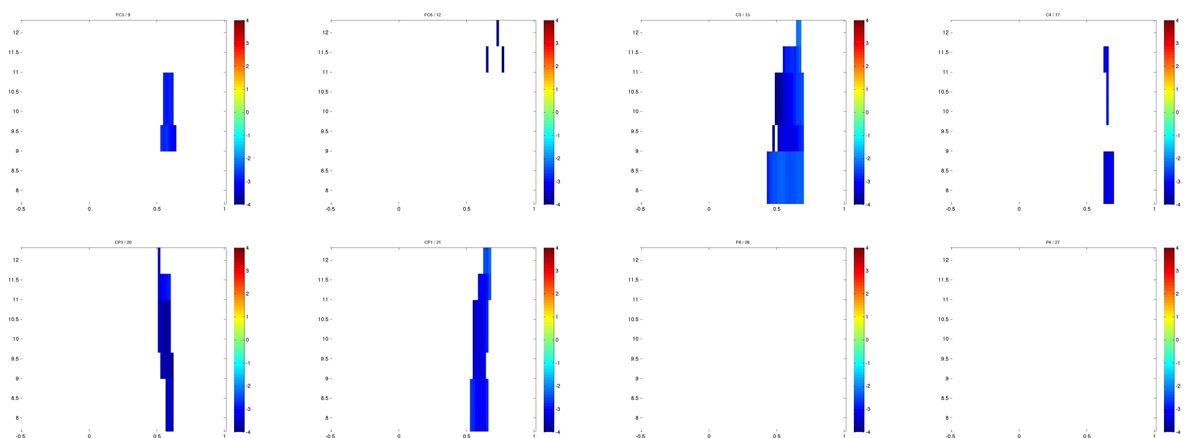


Figure 2.32: θ-Criterion Violation: Lower Beta band (13-20Hz) masked stats TFR

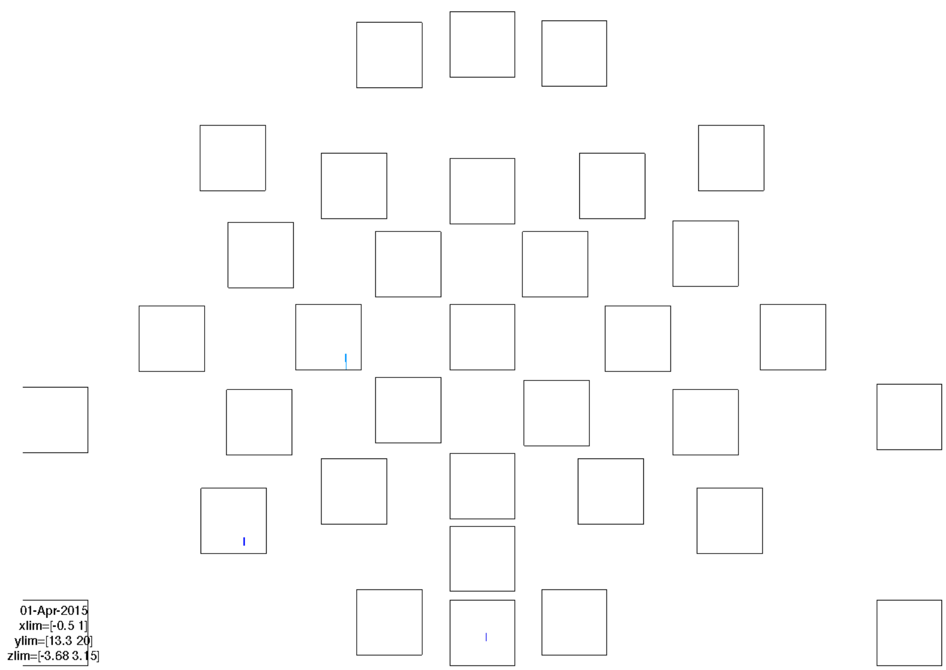


Figure 2.33: θ-Criterion Violation: Lower Beta band (13-20Hz) masked stats TFR, significant channels

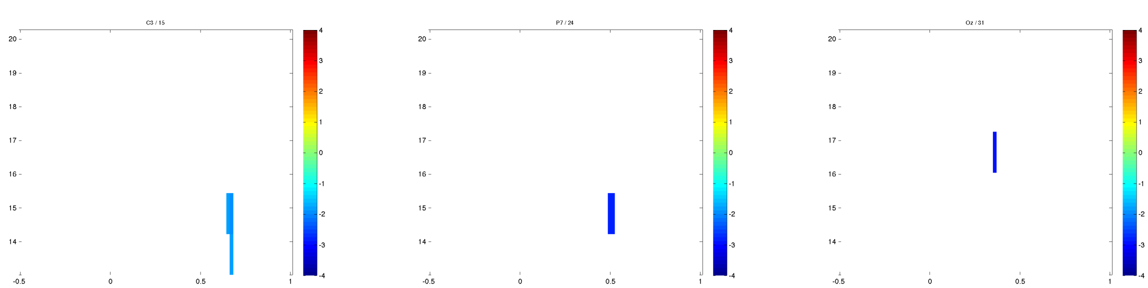


Figure 2.34: θ-Criterion Violation: Upper Beta band (21-30Hz) masked stats TFR

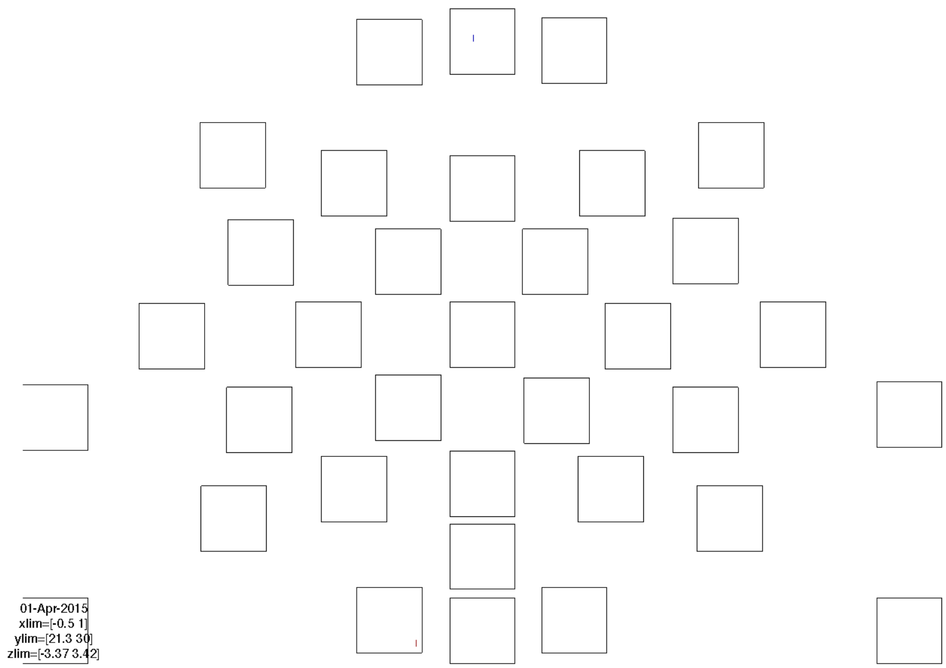


Figure 2.35: θ-Criterion Violation: Upper Beta band (21-30Hz) masked stats TFR, significant channels

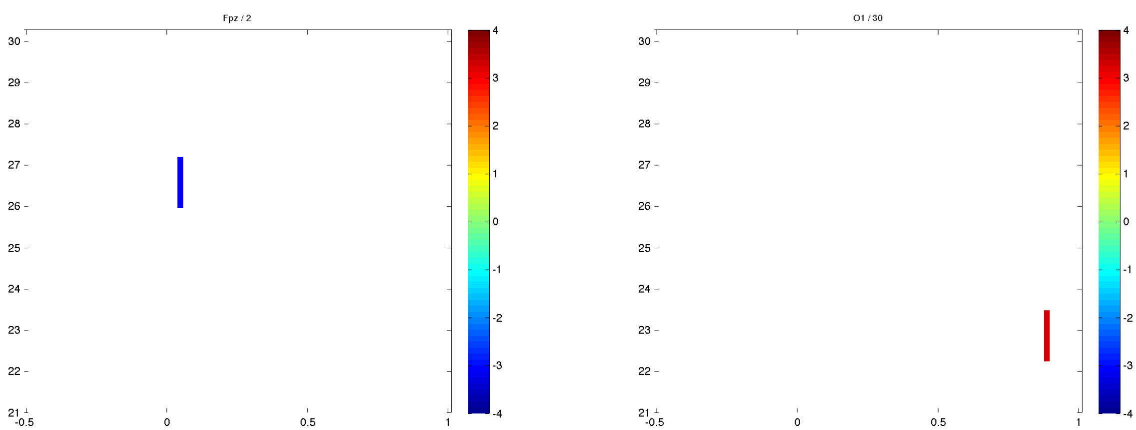


Figure 2.36: θ-Criterion Violation: Gamma band (31-40Hz) masked stats TFR

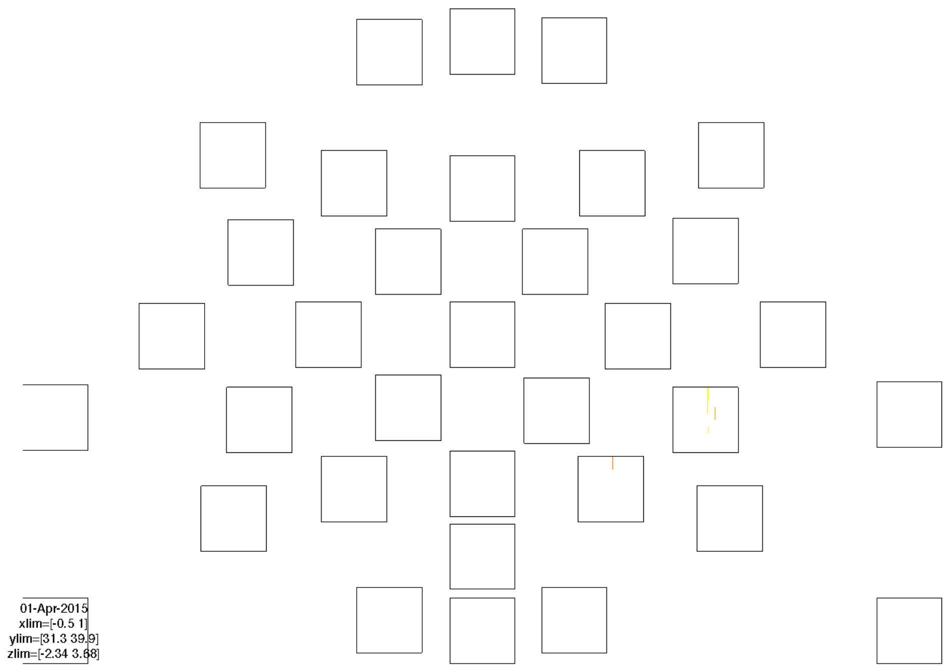
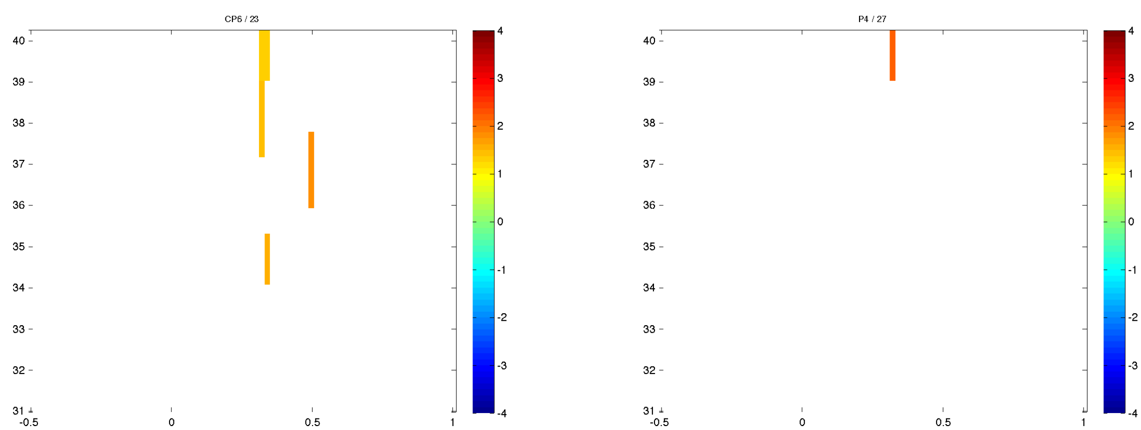


Figure 2.37: θ-Criterion Violation: Gamma band (31-40Hz) masked stats TFR, significant channels



short-distance dependency vs. Control: *wh*-filler

CONTROL	The cameraman knew *that* *the* former mayor would *honor* *the* soldiers before the fireworks.
WHS	The cameraman knew *who* *would* honor the soldiers before *the* fireworks.

ERPs

In a comparison of the *wh*-complementizer *who* in the short-distance dependency condition vs. the complementizer *that* in the Control condition, there is a negative going deflection following the *wh*-word, which is visible in 100ms time slices at 300 and 400ms, and again from 700-900ms. Cluster-based permutation tests with cluster α and FWER $\alpha = 0.08$ reveal broad, marginally significant clusters of (slightly right-biased) negative activity, between ∼300-400ms (Fig. 2.42).

Figure 2.38: ‘Who’, short-distance dependency vs. *that*, Control: ERPs

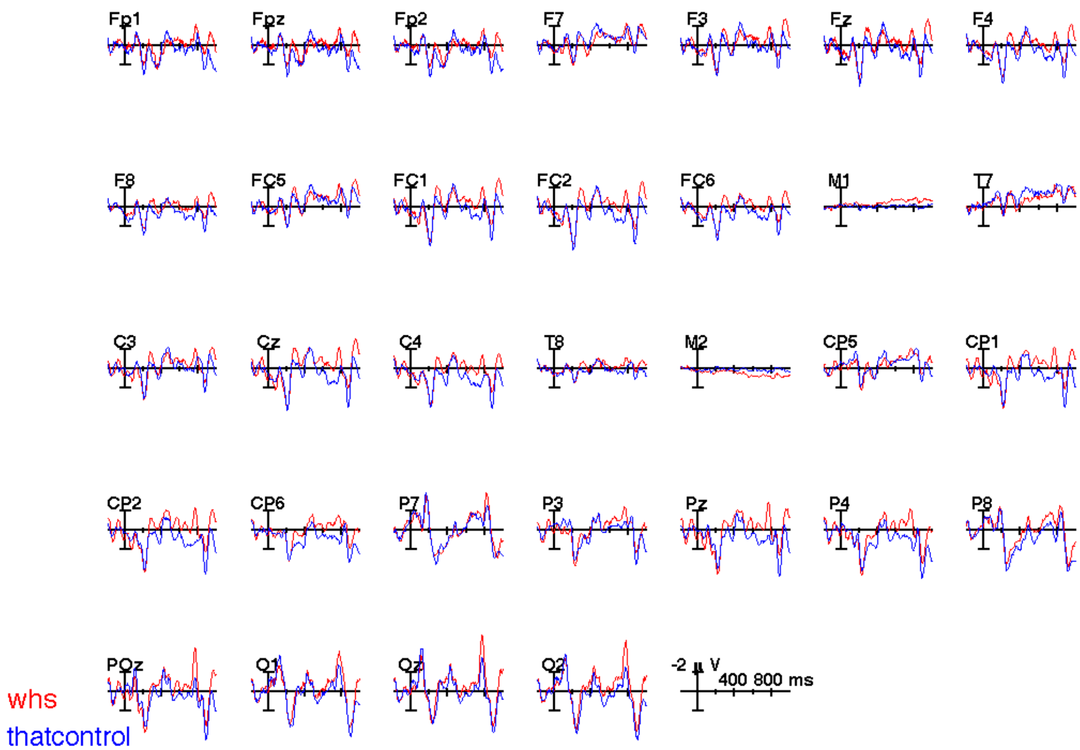
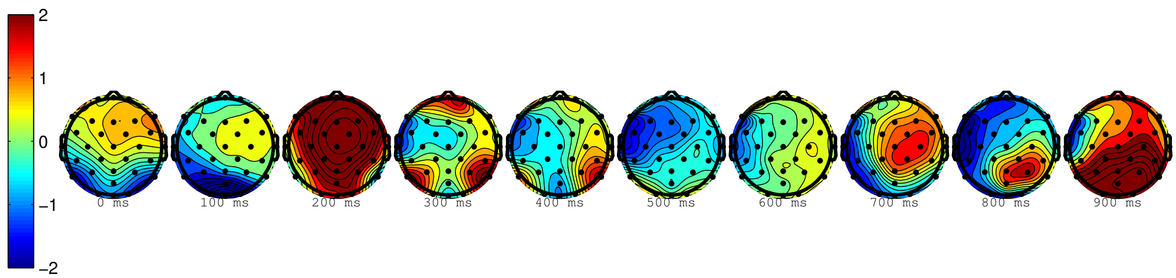
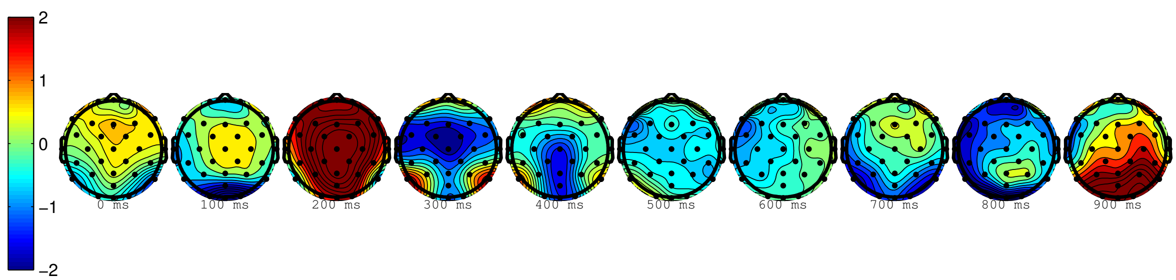


Figure 2.39: ‘Who’, short-distance dependency vs. *that*, Control: topoplots

that Control



Who, short-distance dependency



Difference plots

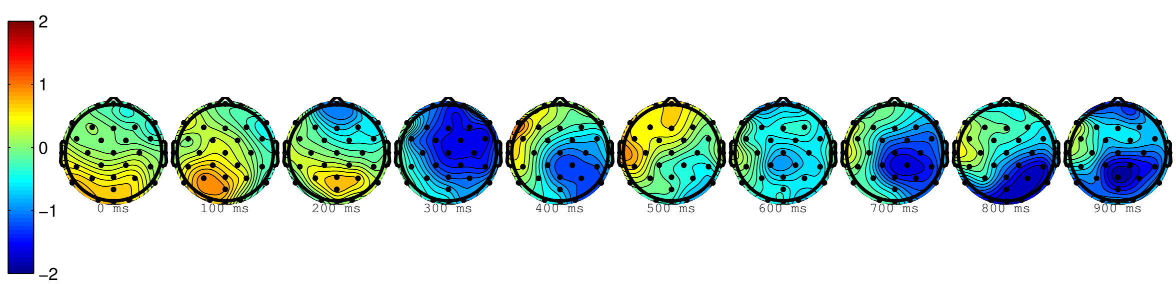


Figure 2.40: 'Who', short-distance dependency vs. *that*, Control: t_{max} permutation tests

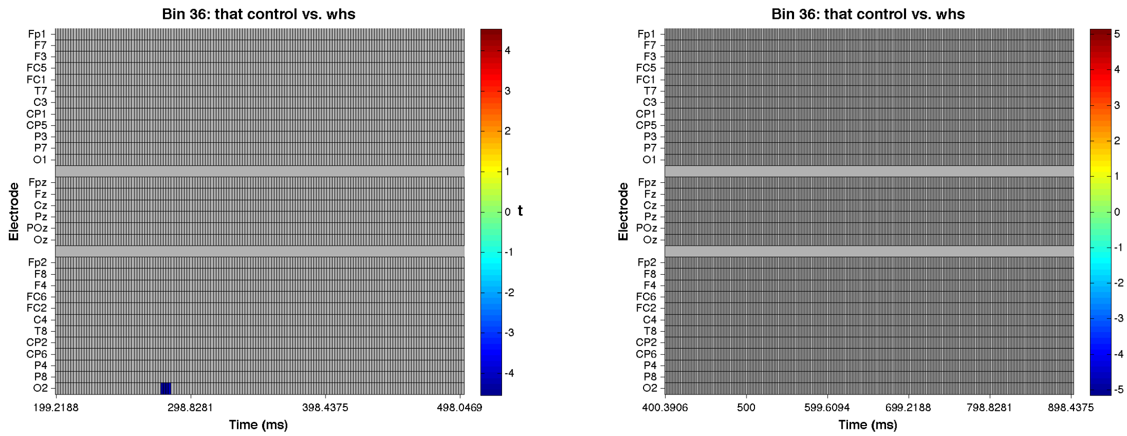


Figure 2.41: 'Who', short-distance dependency vs. *that*, Control: cluster mass permutation tests

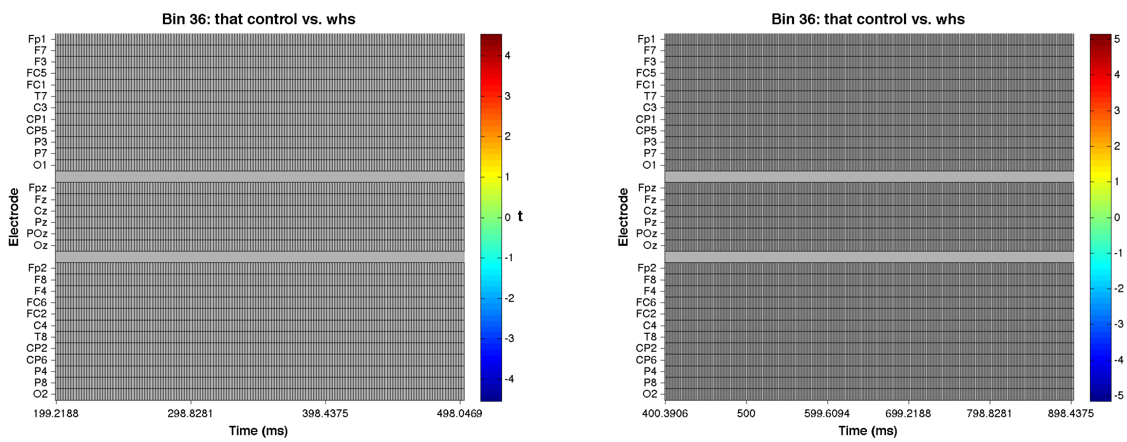
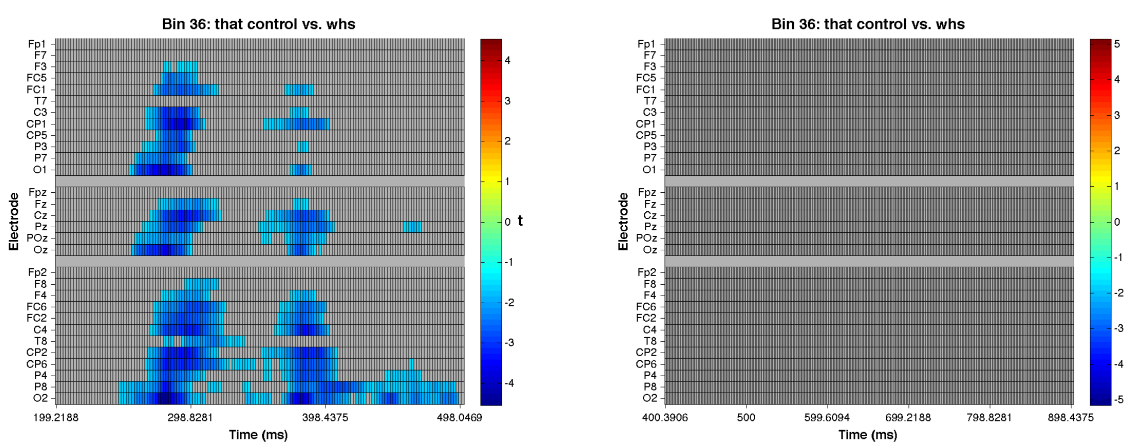


Figure 2.42: 'Who', short-distance dependency vs. *that*, Control: cluster mass permutation tests (cluster alpha=0.8)



TFRs

Comparing the *wh-* complementizer *who* in the short-distance Dependency condition to the complementizer *that* in the controlcondition, there is a significant increase in 31-32Hz activity in right centro parietal areas at ∼200ms, followed by an increase in 34-38Hz activity at ∼300ms. This is followed by increases in 34-38Hz in fronto-central areas between ∼550 and ∼800ms, and finally an increase in 33Hz activity at ∼950ms.

Overall, there is a significant increase in gamma band activity in right centro parietal areas at ∼200-300ms (channel CP6, Cz), followed by an additional increase in right fronto-central areas at points between ∼600 and ∼900ms.

Figure 2.43: short-distance dependency, *wh*-filler: TFR

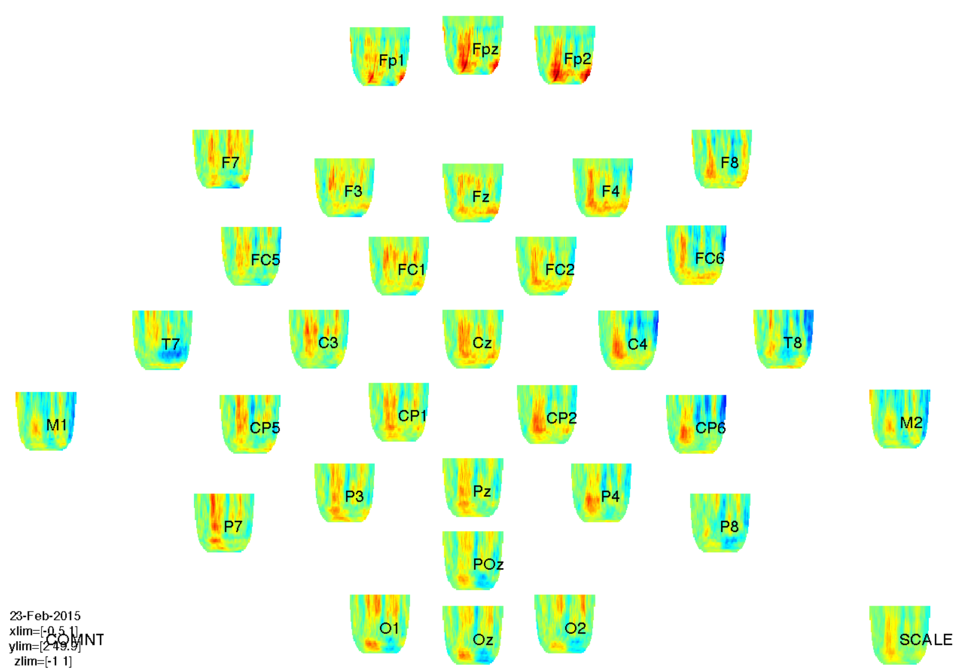


Figure 2.44: short-distance dependency, *wh*-filler: Gamma band (31-40Hz) masked stats TFR

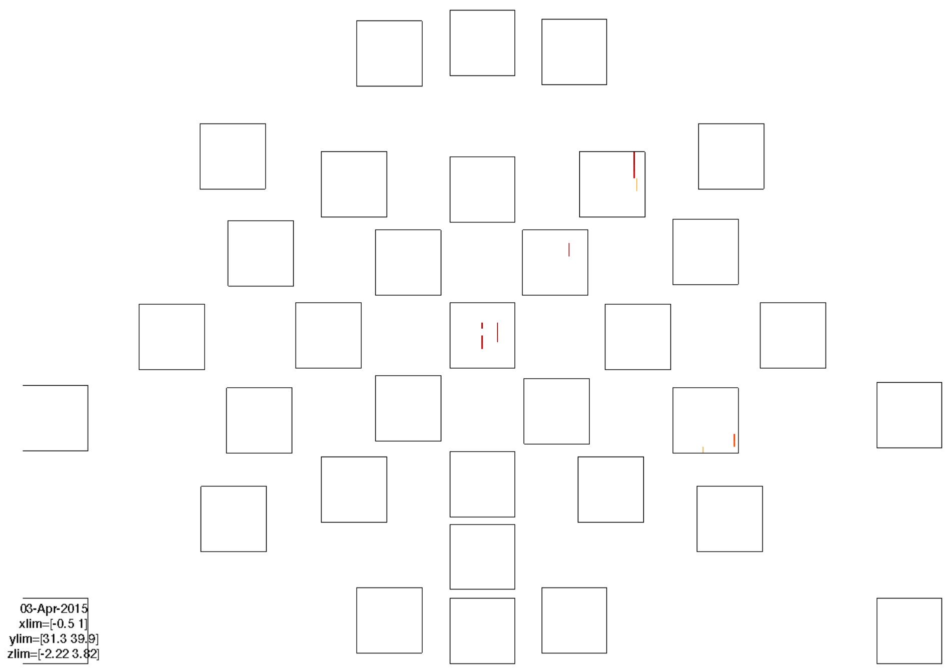
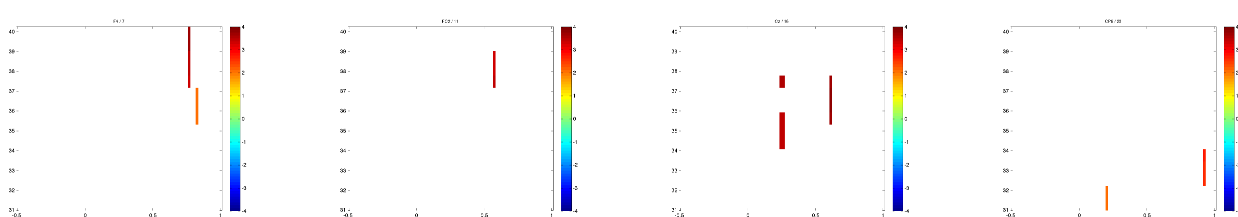


Figure 2.45: short-distance dependency, *wh*-filler: Gamma band (31-40Hz) masked stats TFR, significant channels



short-distance dependency vs. Control: gap resolution

CONTROL	The cameraman knew *that* *the* former mayor would *honor* *the* soldiers before the fireworks.
WHS	The cameraman knew *who* *would* honor the soldiers before *the* fireworks.

ERPs

Comparing the modal (e.g., *could*) of the short-distance dependency to the article *the* of the Control condition, there is a negative going deflection following the modal of the short-distance dependency, which is visible in 100ms time slices from 100-400ms, and again at 900ms. Results of both the t_{max} and cluster-based permutation tests reveal significant negative activity in early time windows, in broad (slightly more posterior) areas. The t_{max} test finds significant negative activity from ∼300-350ms in central posterior channels (Fig. 2.48), and the cluster-based tests reveal significant bilateral clusters of negative activity from ∼275-425ms, which extend from frontal to posterior channels (Fig. 2.49).

Figure 2.46: Modal, short-distance dependency vs. *the*, Control: ERPs

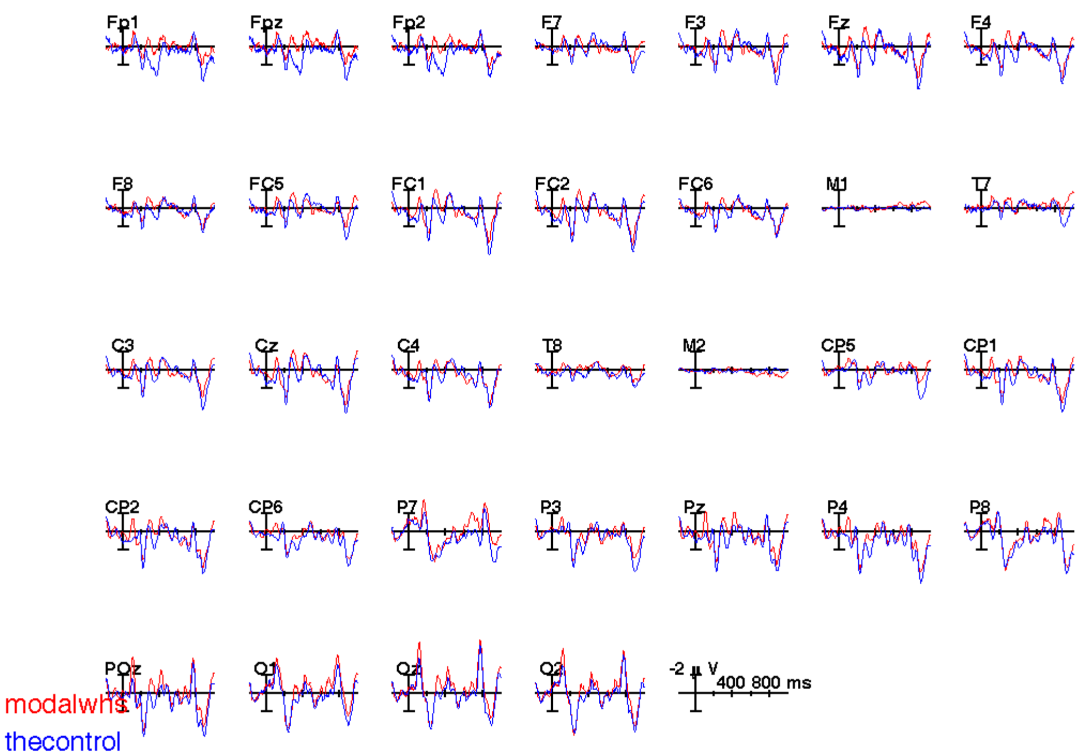
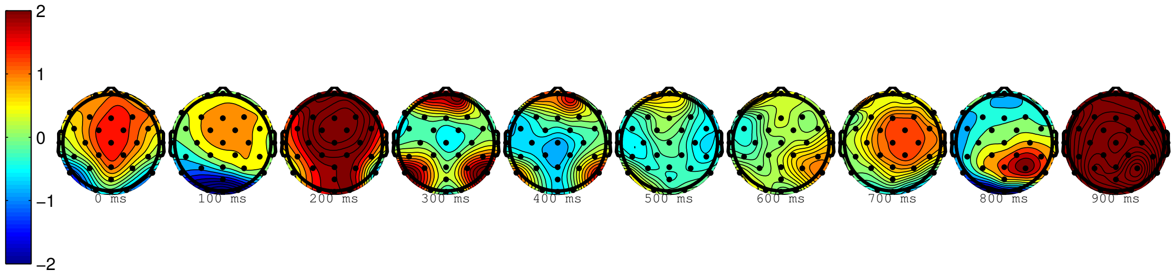
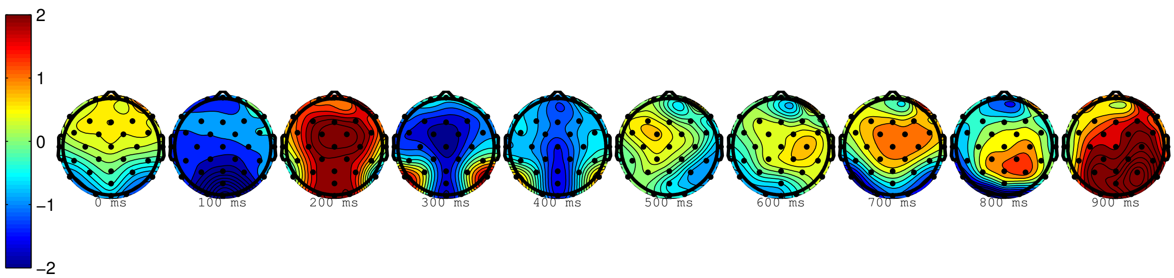


Figure 2.47: Modal, short-distance dependency vs. *the*, Control: topoplots

the Control



Modal, short-distance dependency



Difference plots

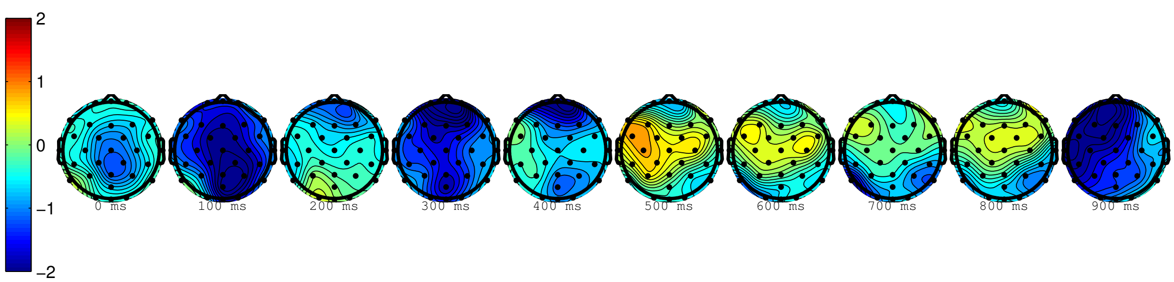


Figure 2.48: Modal, short-distance dependency vs. *the*, Control: t_{max} permutation tests

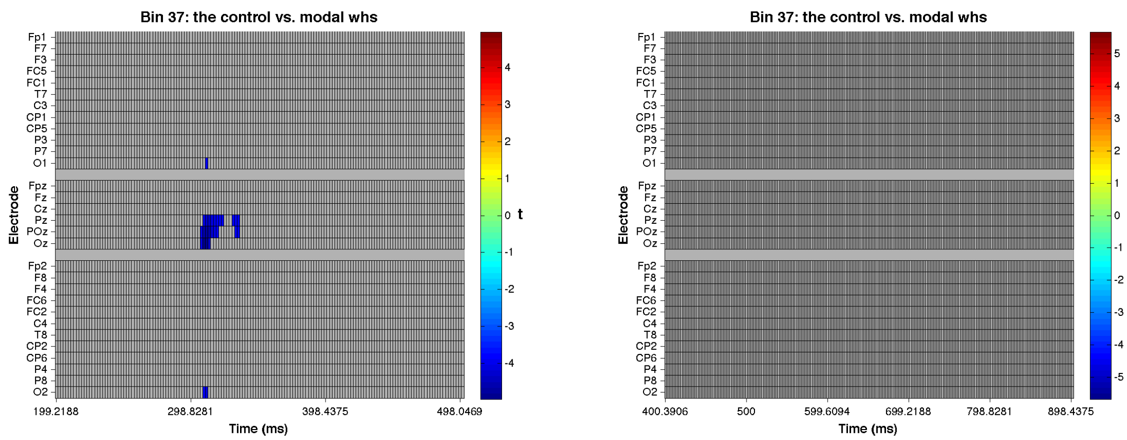
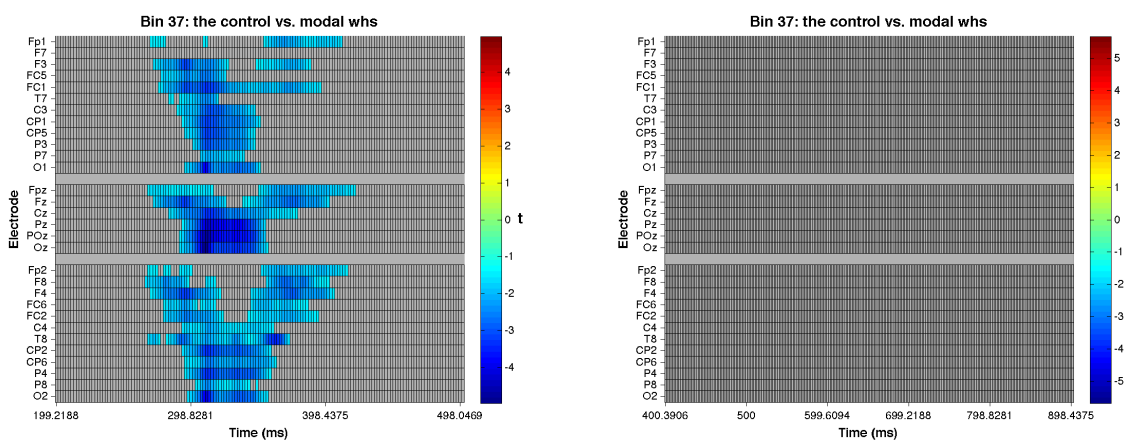


Figure 2.49: Modal, short-distance dependency vs. *the*, Control: cluster mass permutation tests



TFRs

Comparing the modal (e.g., *could*) which represents the point of gap-resolution for the short-distance dependency condition to the first word of the subordinate clause (*the*) in the Control condition, there is a significant increase in 4-7Hz (Theta band) activity in the dependency condition, in left occipital and parietal areas. This increases begins immediately at the onset of the critical word, and lasts until ∼500ms. In addition, there is also a significant increase in 21-27Hz and 30Hz (Upper Beta) activity in mastoid channels bilaterally and in the occipito-parietal channel 'POz' at ∼800ms.

Figure 2.50: short-distance dependency, gap resolution: TFR

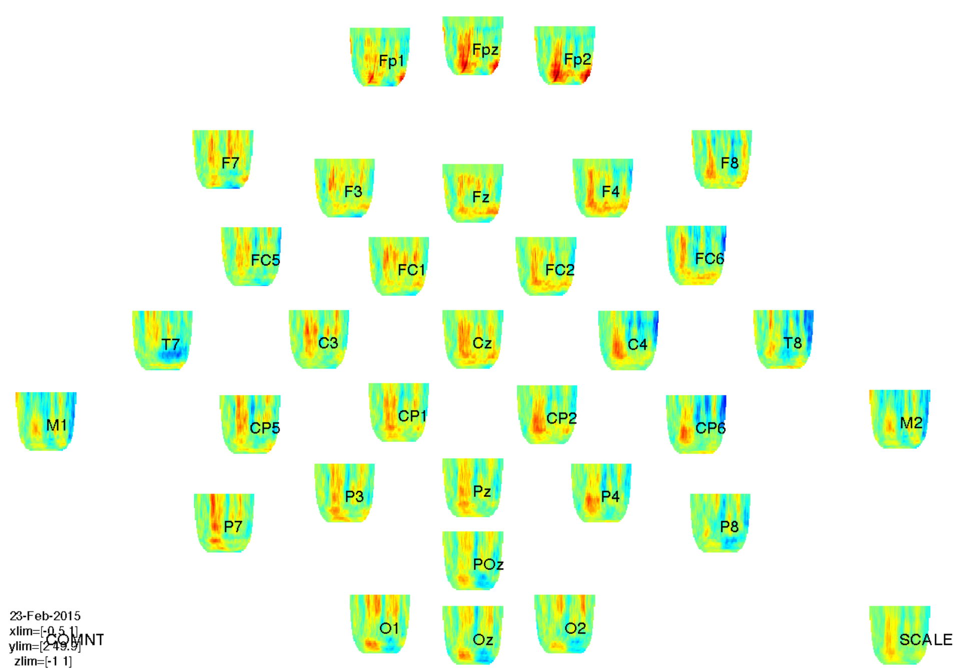


Figure 2.51: short-distance dependency, gap resolution: Theta band (4-7Hz) masked stats TFR

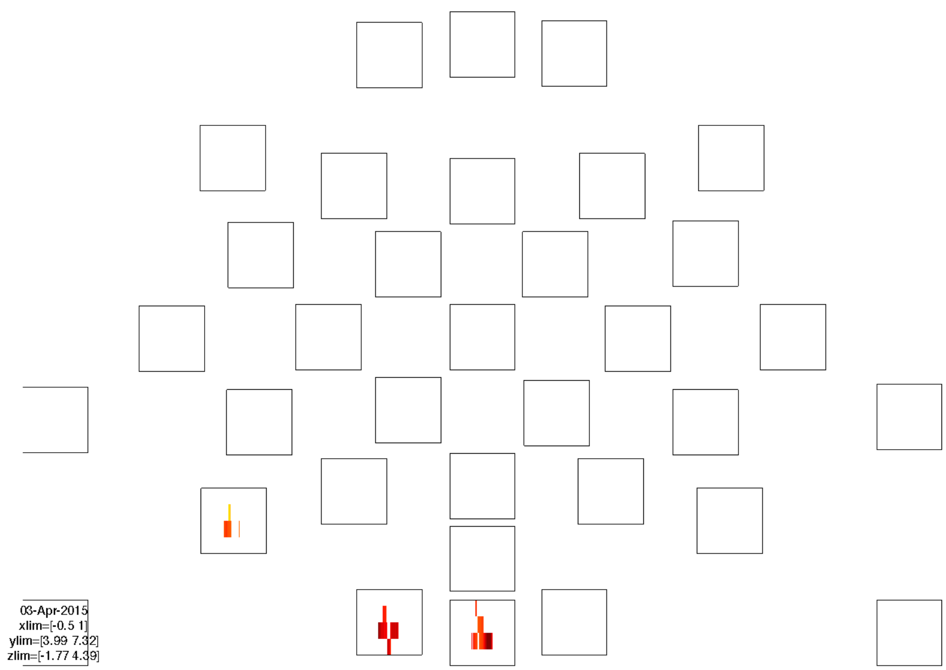


Figure 2.52: short-distance dependency, gap resolution: Theta band (4-7Hz) masked stats TFR, significant channels

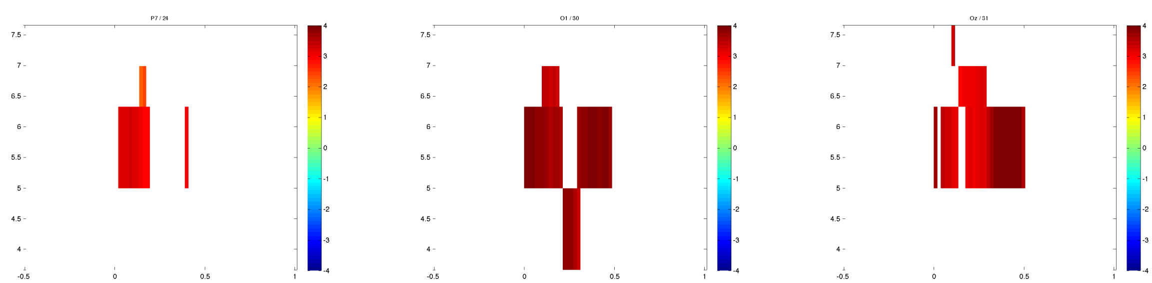


Figure 2.53: short-distance dependency, gap resolution: Upper Beta band (21-30Hz) masked stats TFR

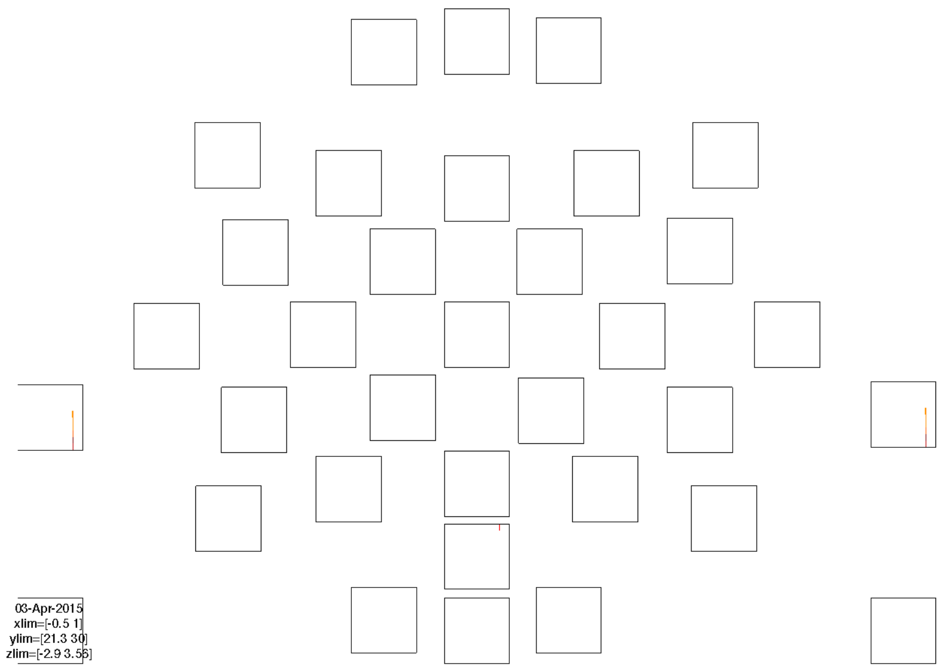
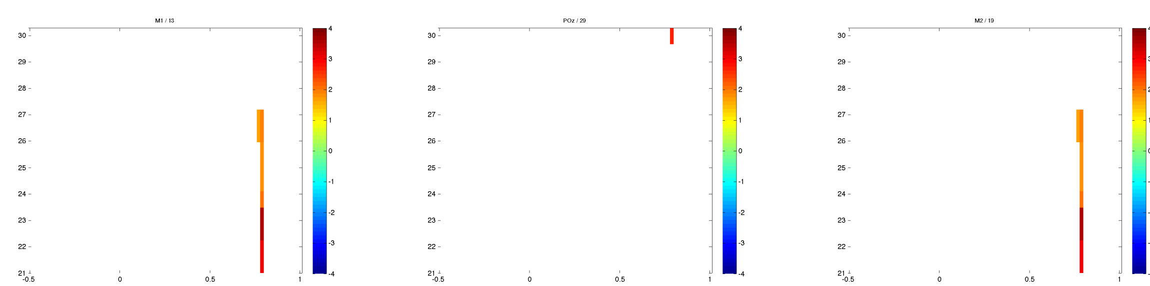


Figure 2.54: short-distance dependency, gap resolution: Upper Beta band (21-30Hz) masked stats TFR, significant channels



long-distance dependency vs. Control: *wh*-filler

CONTROL	The cameraman knew *that* *the* former mayor would *honor* *the* soldiers before the fireworks.
WHO	The cameraman knew *who* *the* former mayor would honor *before* the fireworks.

ERPs

In a comparison of the *wh*-complementizer *who* in the long-distance dependency condition vs. the complementizer *that* in the Control condition, there is a positive going deflection following the *wh*-word, which is visible in 100ms time slices at 200 and 400-800ms. This positivity is significant in left hemisphere channels (mostly temporal) between ∼400-900ms according to the t_{max} permutation tests (Fig. 2.57), and is found to represent broad clusters of significant positive activity in bilateral (slightly more anterior) areas, according to the cluster permutation tests (Fig. 2.58).

Figure 2.55: 'Who', long-distance dependency vs. *that* control: ERPs

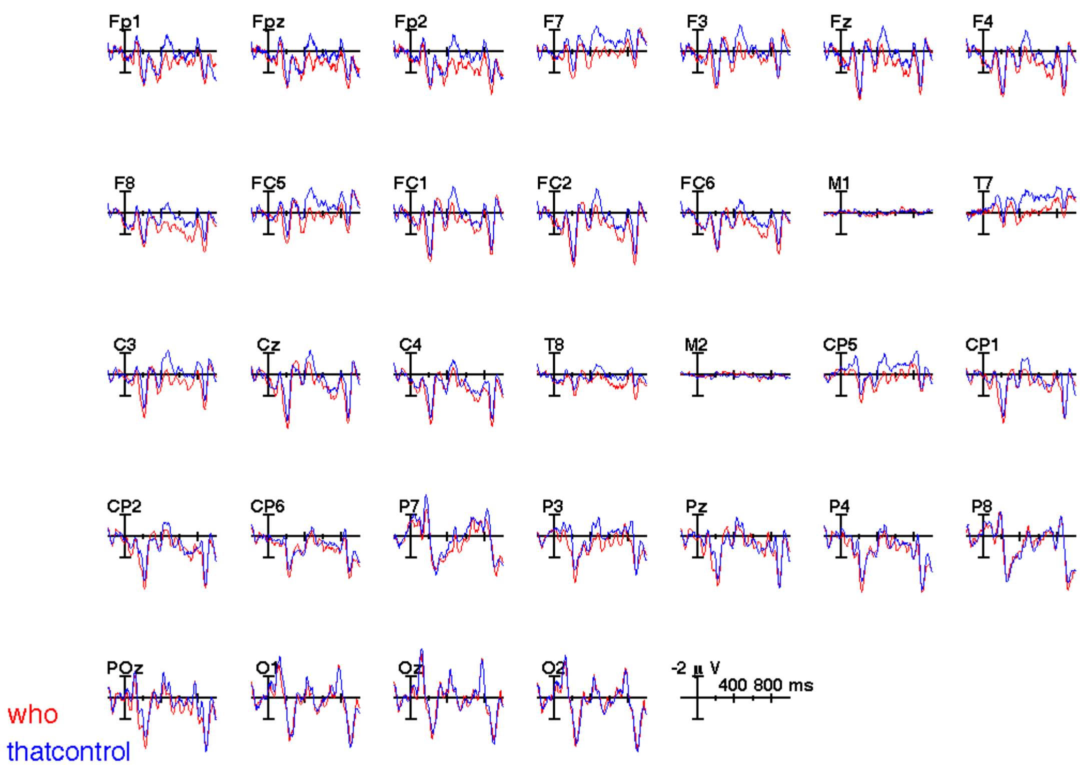
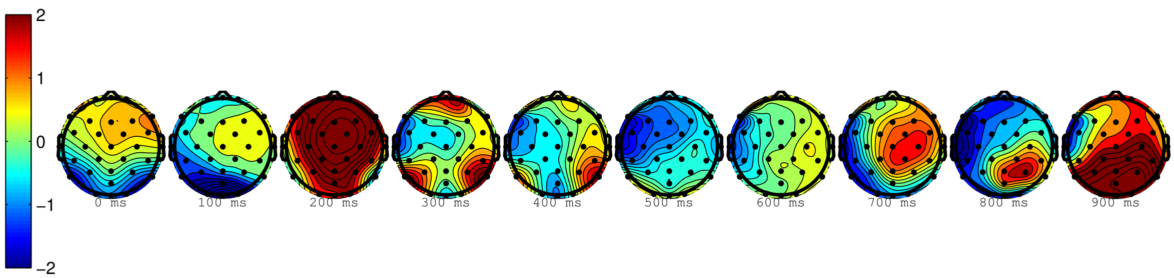
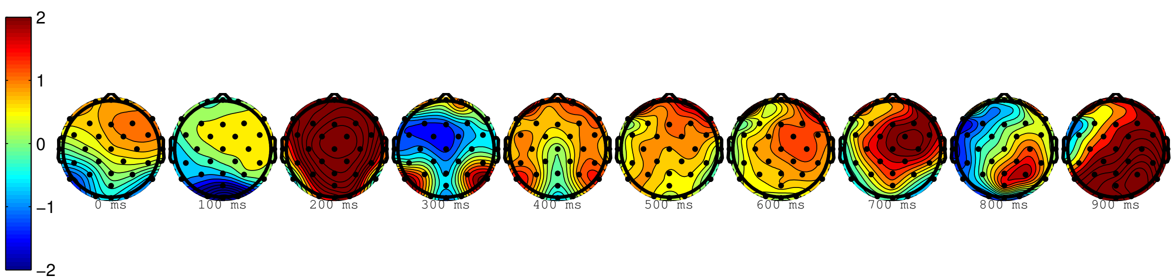


Figure 2.56: ‘Who’, long-distance dependency vs. *that* control: topoplots

that control



Who, long-distance dependency



Difference plots

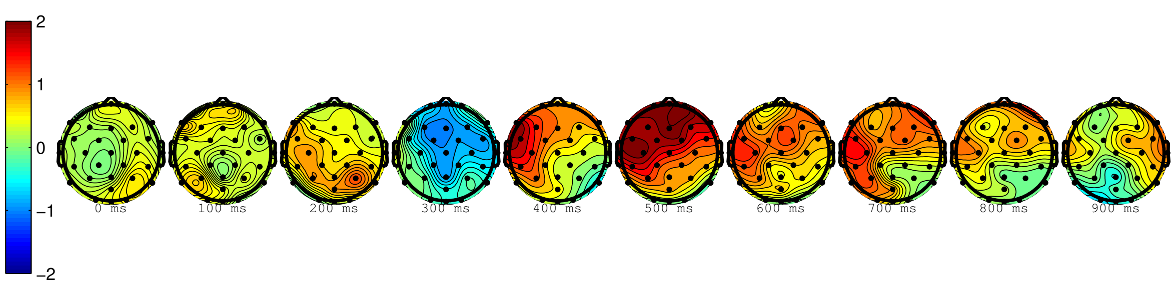


Figure 2.57: ‘Who’, long-distance dependency vs. *that* control: t_{max} tests

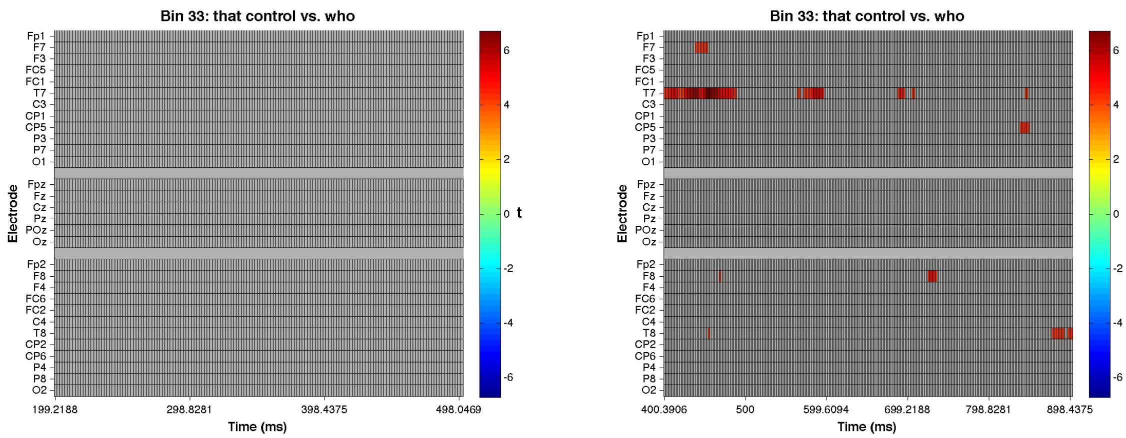
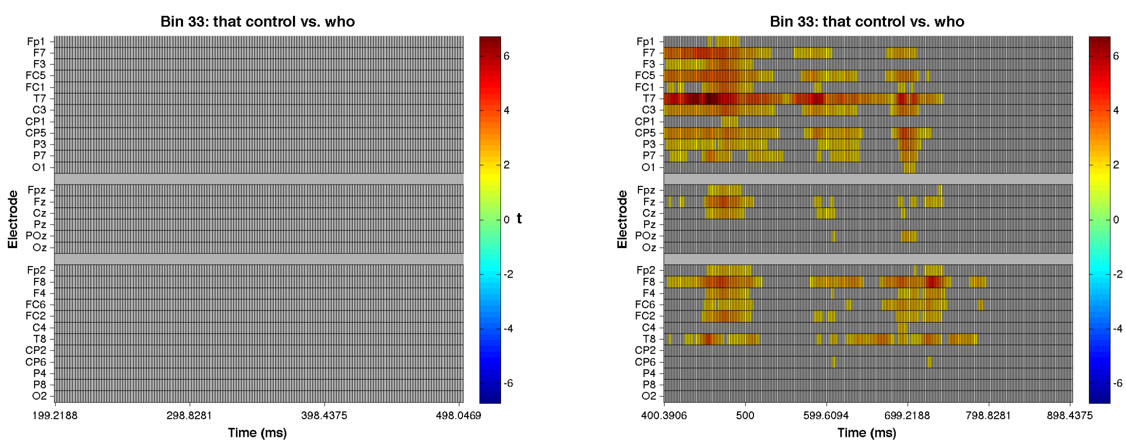


Figure 2.58: ‘Who’, long-distance dependency vs. *that* control: cluster mass permutation tests



TFRs

Comparing the *wh*-complementizer *who* in the long-distance dependency condition to the complementizer *that* in the Control condition, there is a significant increase in 20Hz (Middle Beta) activity in right frontal areas (channel 'F8') at ~850ms.

Figure 2.59: long-distance dependency, *wh*-filler: TFR

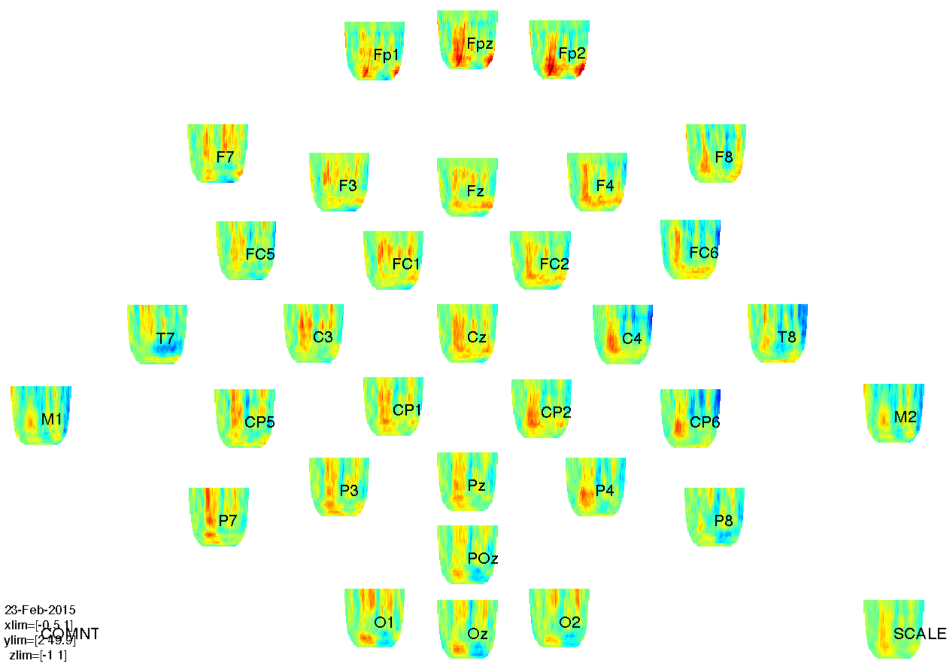


Figure 2.60: long-distance dependency, *wh*-filler: Lower Beta band (13-20Hz) masked stats TFR

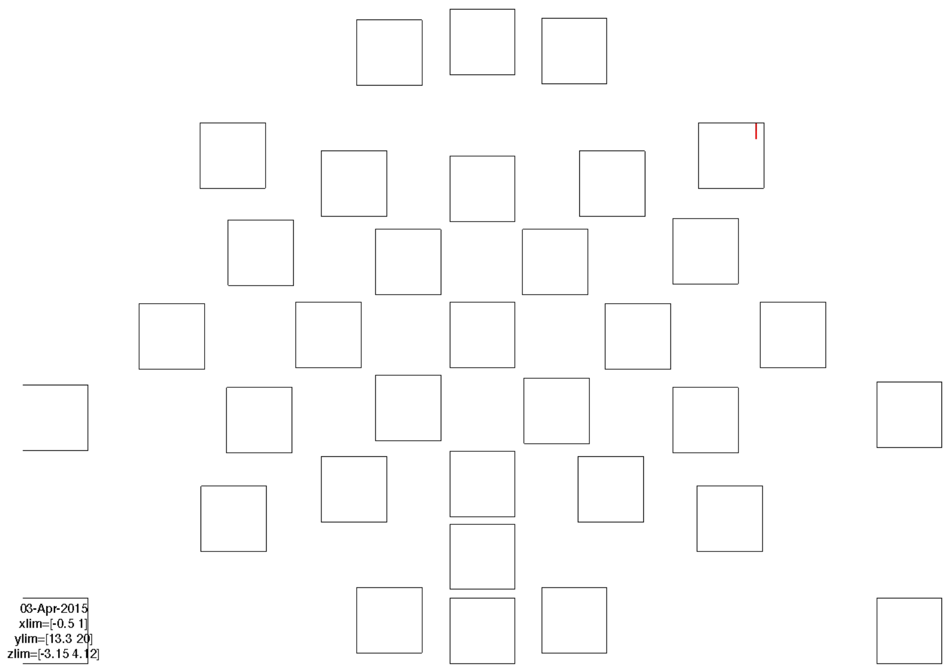
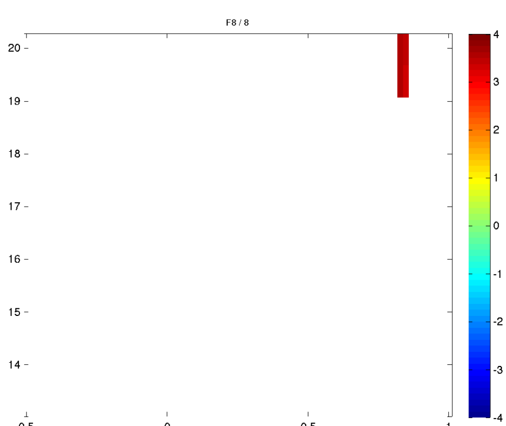


Figure 2.61: long-distance dependency, *wh*-filler: Lower Beta band (13-20Hz) masked stats TFR, significant channels



long-distance dependency vs. Control: first word of dependency

CONTROL	The cameraman knew *that* *the* former mayor would *honor* *the* soldiers before the fireworks.
WHO	The cameraman knew *who* *the* former mayor would honor *before* the fireworks.

ERPs

Comparing the article *the* of the long-distance dependency to the article *the* of the Control condition, there is a negative going deflection following the article of the Long-distance dependency, which is visible at 300 and 400ms, and again at 900ms. According to t_{max} permutation tests, the early portion of this visible negativity is significant in left frontal channel 'FC5' at ∼325ms (Fig. 2.64), and results of the cluster-based permutation tests reveal large (left anterior-biased) clusters of negative-going activity, from ∼250-425ms (Fig. 2.65).

Figure 2.62: *the*, long-distance dependency vs. *the*, Control: ERPs

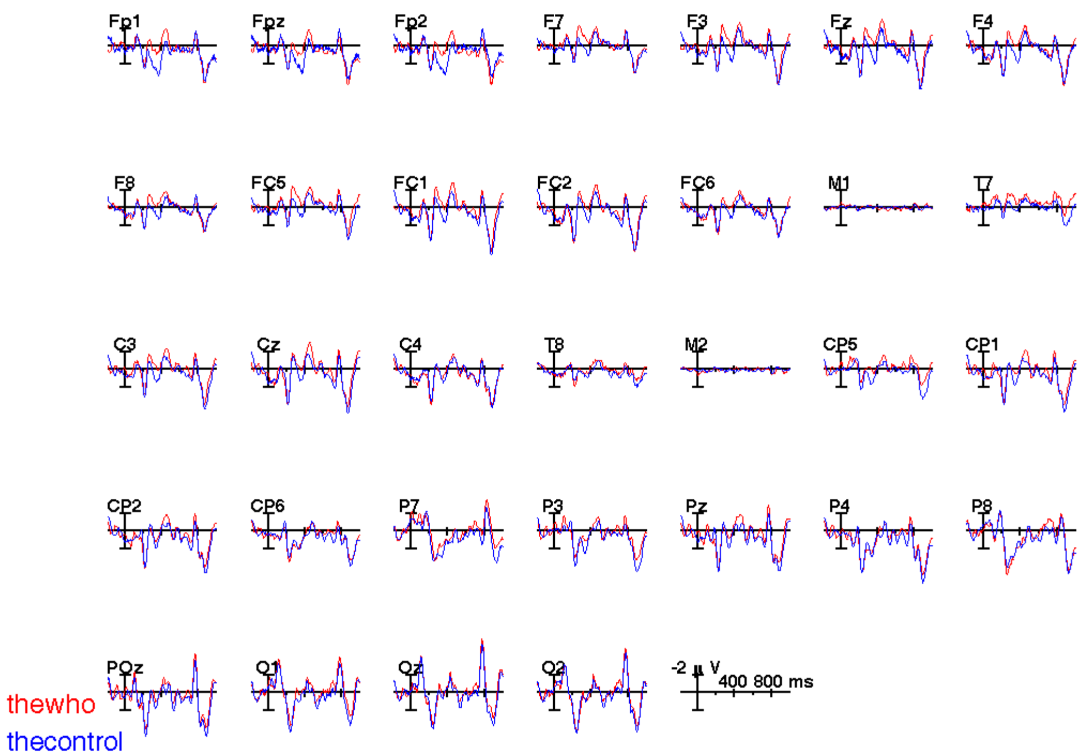
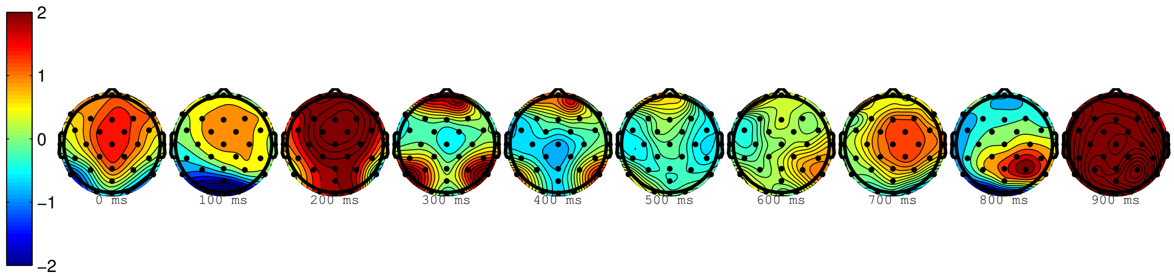
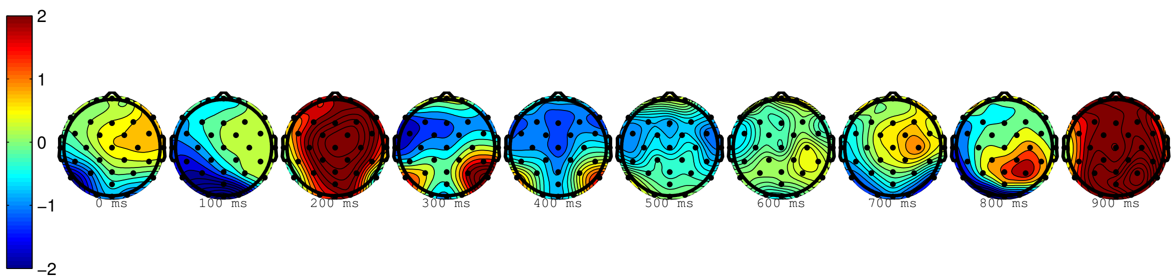


Figure 2.63: *the*, long-distance dependency vs. *the*, Control: topoplots

the, Control



the, long-distance dependency



Difference plots

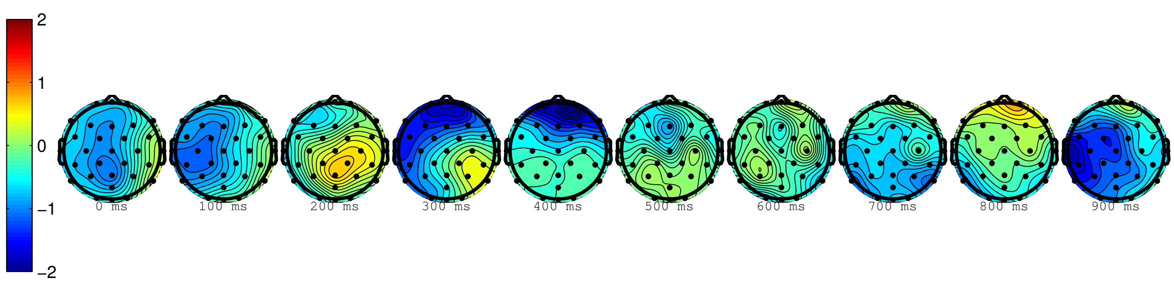


Figure 2.64: *the*, long-distance dependency vs. *the*, Control: t_{max} tests

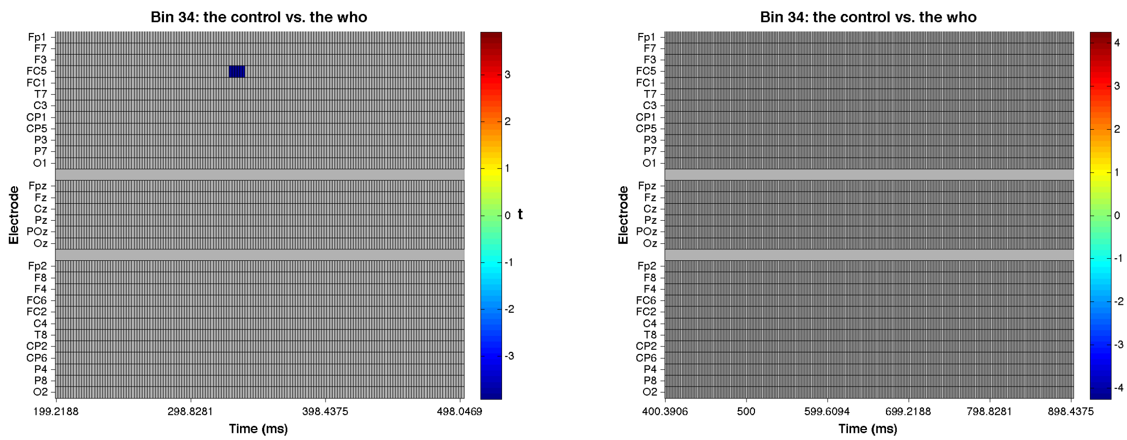
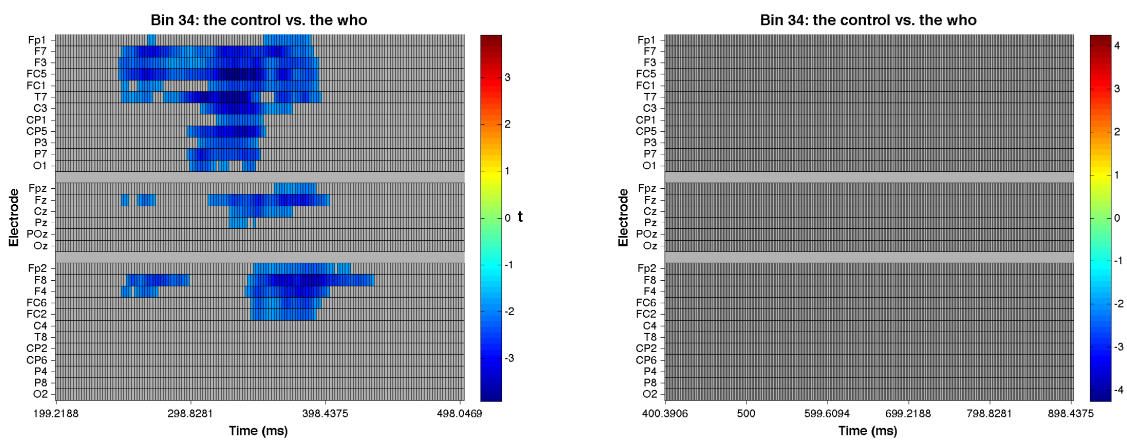


Figure 2.65: *the*, long-distance dependency vs. *the*, Control: cluster mass permutation tests



TFRs

Comparing the article *the* of the long-distance dependency to the article *the* of the Control condition, there is a significant increase in 20Hz (Middle Beta) activity in right frontal areas (channel 'F8') at ~200ms.

Figure 2.66: *the*, long-distance dependency vs. *the*, Control: TFR

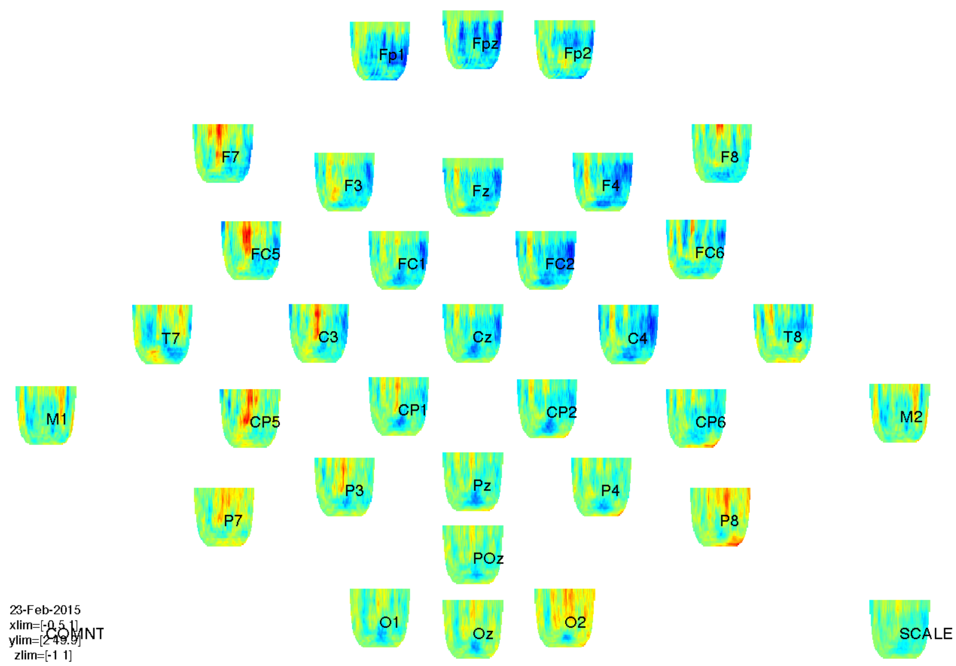


Figure 2.67: *the*, long-distance dependency vs. *the*, Control: Lower Beta band (13-20Hz) masked stats TFR

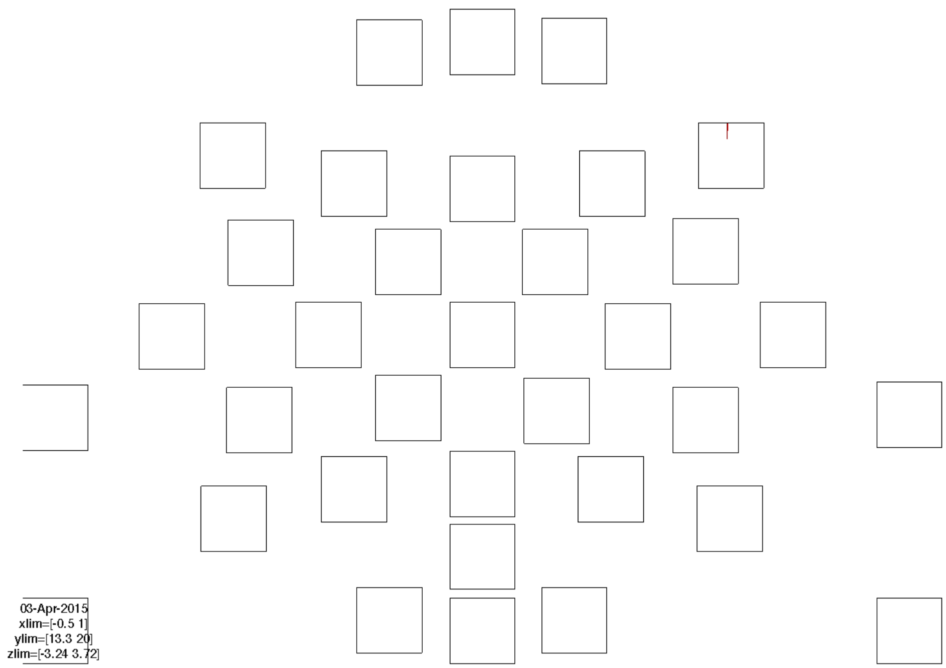
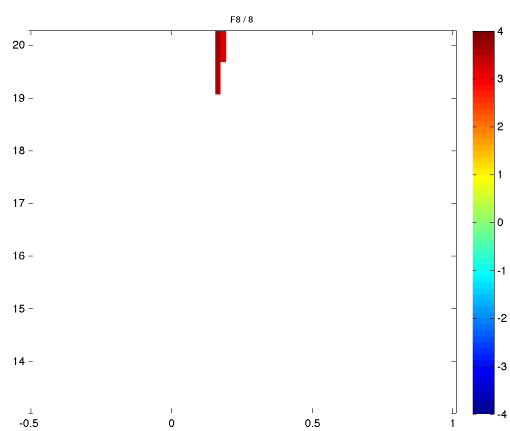


Figure 2.68: *the*, long-distance dependency vs. *the*, Control: Lower Beta band (13-20Hz) masked stats TFR, significant channels



long-distance dependency vs. Control: DO gap resolution

CONTROL	The cameraman knew *that the* former mayor would *honor* *the* soldiers before the fireworks.
WHO	The cameraman knew *who the* former mayor would honor *before* the fireworks.

ERPs

Finally, comparing the preposition of the adjunct PP of the long-distance dependency condition to the article of the DO of the Control condition, there is a negative going deflection following the long-distance dependency, which is visible at 300ms, and a temporal positivity that lasts from ~400-700ms. According to the t_{max} permutation test, there is a significant positivity in left anterior and temporal channels between ~500-800ms (Fig. 2.71).

Figure 2.69: PP, long-distance dependency vs. DO, Control: ERPs

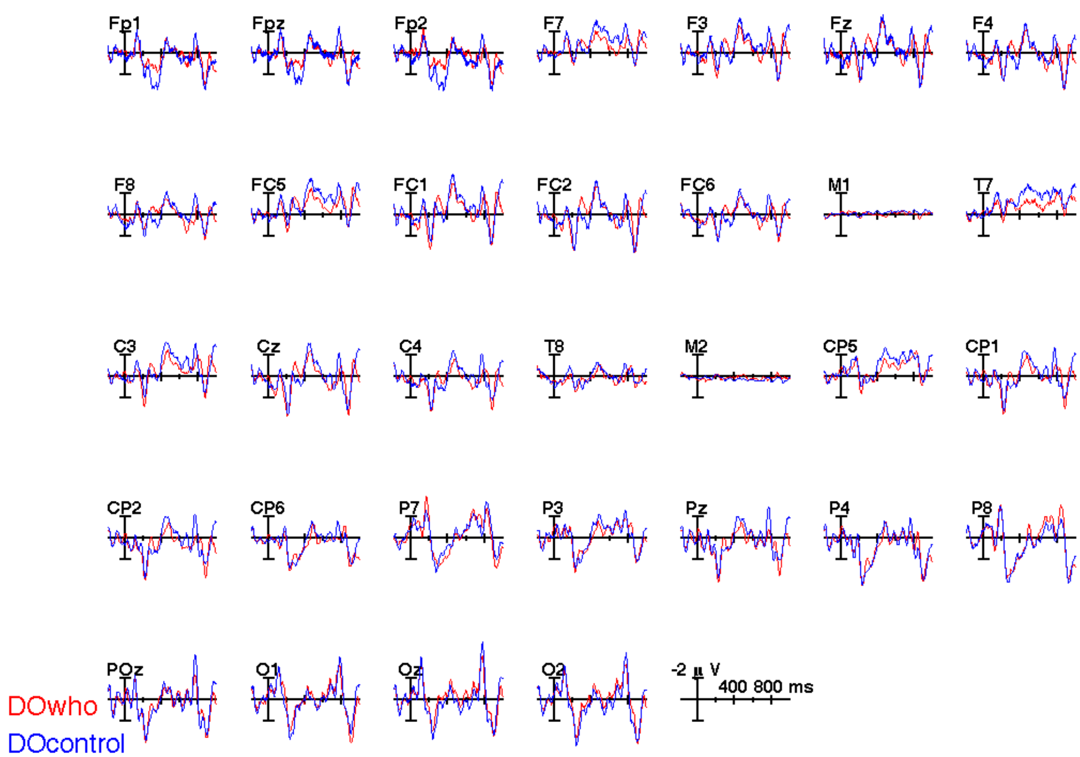
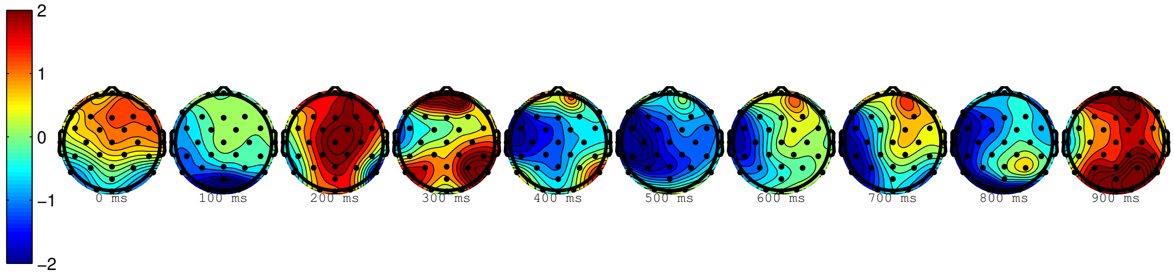
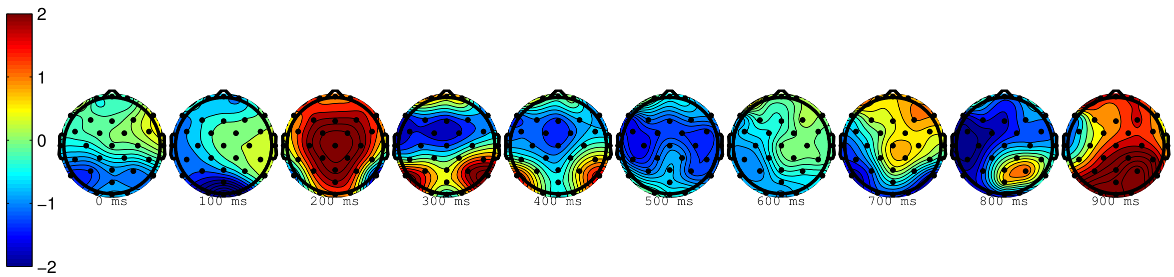


Figure 2.70: PP, long-distance dependency vs. DO, Control: topoplots

DO, Control



PP, long-distance dependency



Difference plots

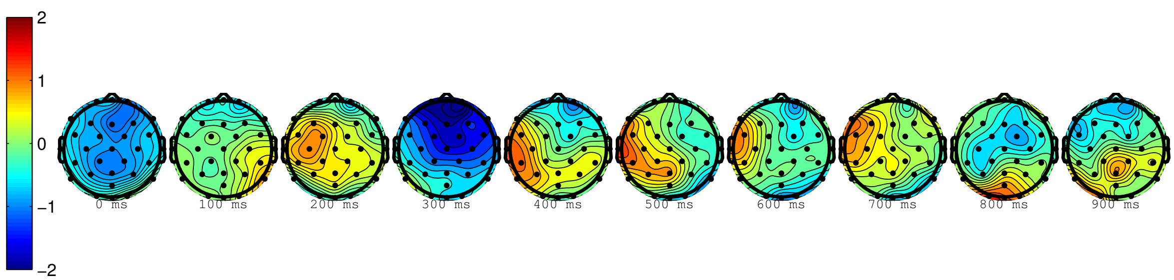


Figure 2.71: PP, long-distance dependency vs. DO, Control control: t_{max} tests

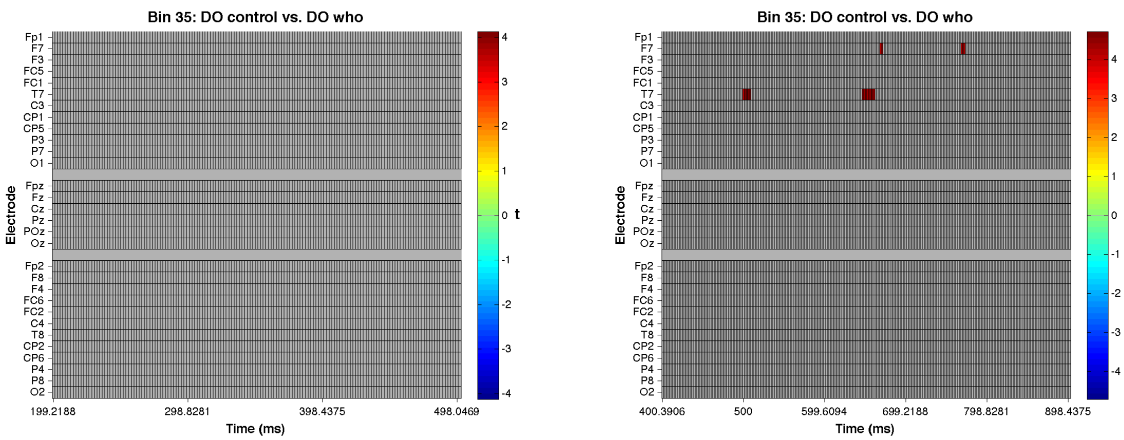
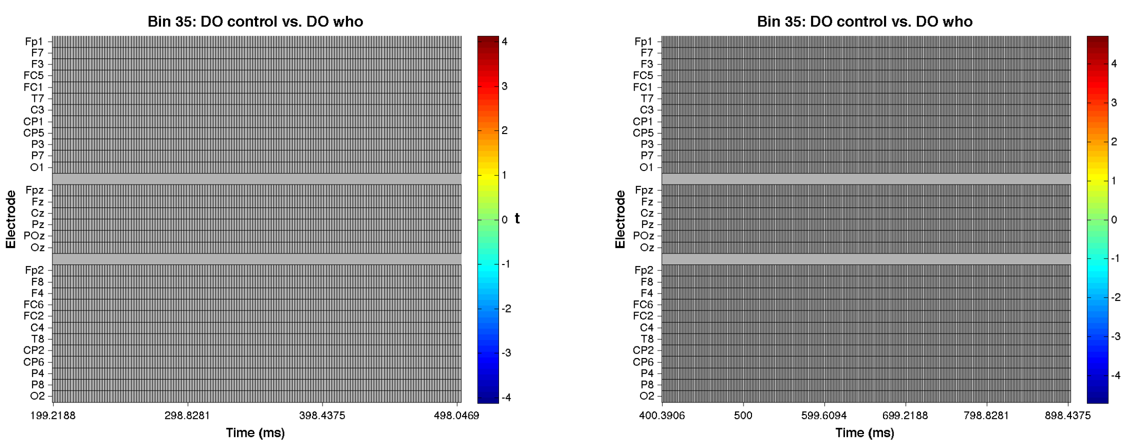


Figure 2.72: PP, long-distance dependency vs. DO, Control control: cluster tests



TFRs

Comparing the preposition of the adjunct PP of the long-distance dependency condition to the article of the DO of the Control condition, there is a significant increase in a broad swath of activity from ∼0-300ms, including an increase in 5-6Hz activity in right temporal and occipital areas, an increase in 14-20Hz activity in bilateral frontal and temporal areas, an increase in 21-30Hz activity in right fronto-central and right parietal areas, an increase in 11-12Hz activity at ∼300ms, in left temporal areas (channel 'T7'), and an increase in 31-40Hz in central and right parietal areas.

Overall, between ∼0 and ∼300ms there is a significant increase in Theta, Alpha, Lower and Upper Beta, and Gamma band activity, in primarily right hemisphere areas (with some increase in Lower Beta activity in left anterior areas).

Figure 2.73: PP, long-distance dependency vs. DO, Control: TFR

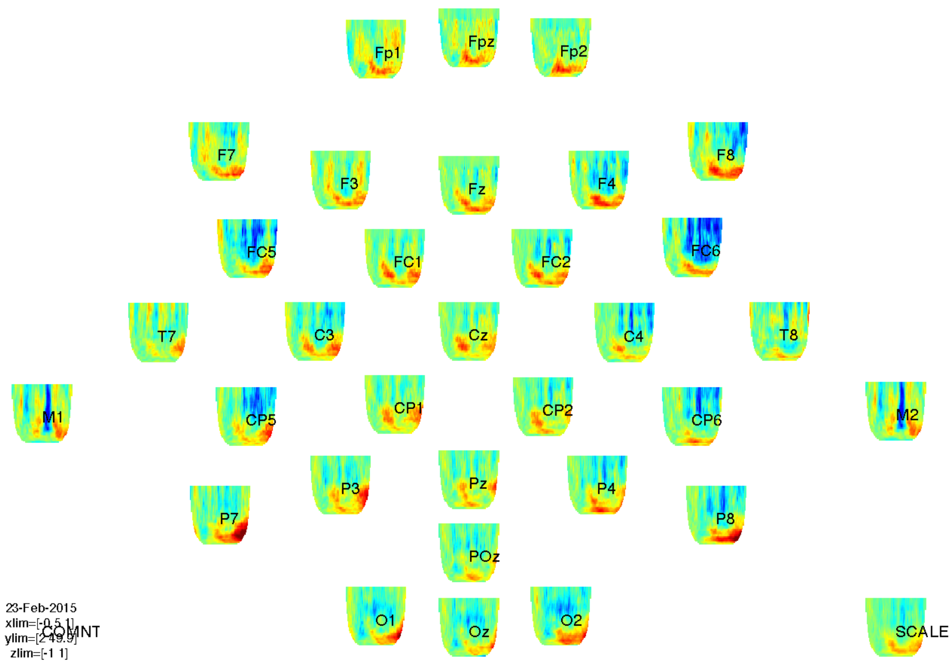


Figure 2.74: PP, long-distance dependency vs. DO, Control: Theta band (4-7Hz) masked stats TFR

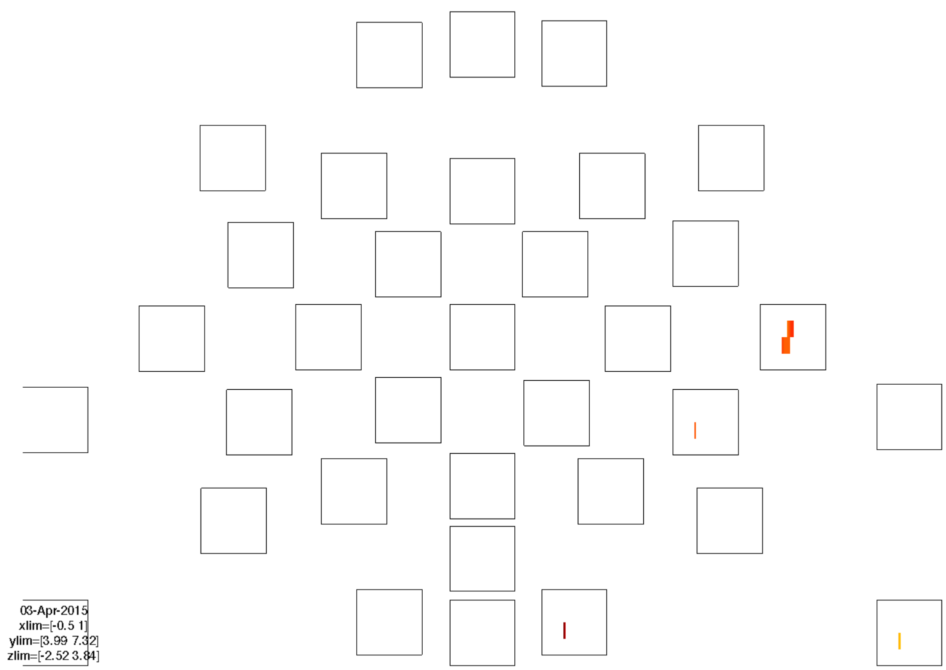


Figure 2.75: PP, long-distance dependency vs. DO, Control: Theta band (4-7Hz) masked stats TFR, significant channels

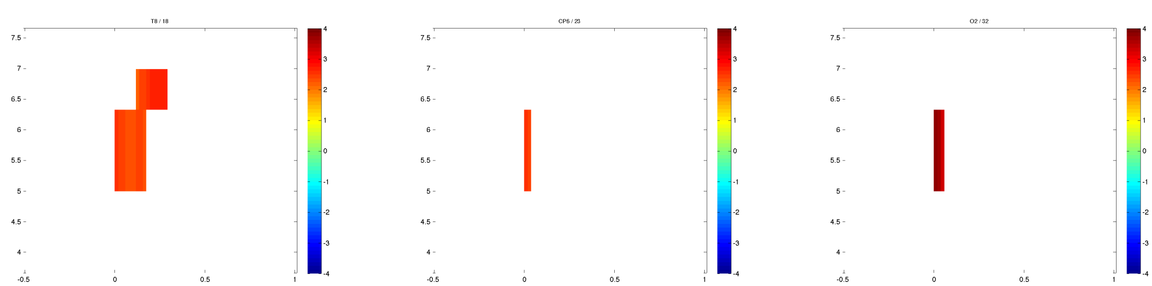


Figure 2.76: PP, long-distance dependency vs. DO, Control: Alpha band (8-12Hz) masked stats TFR

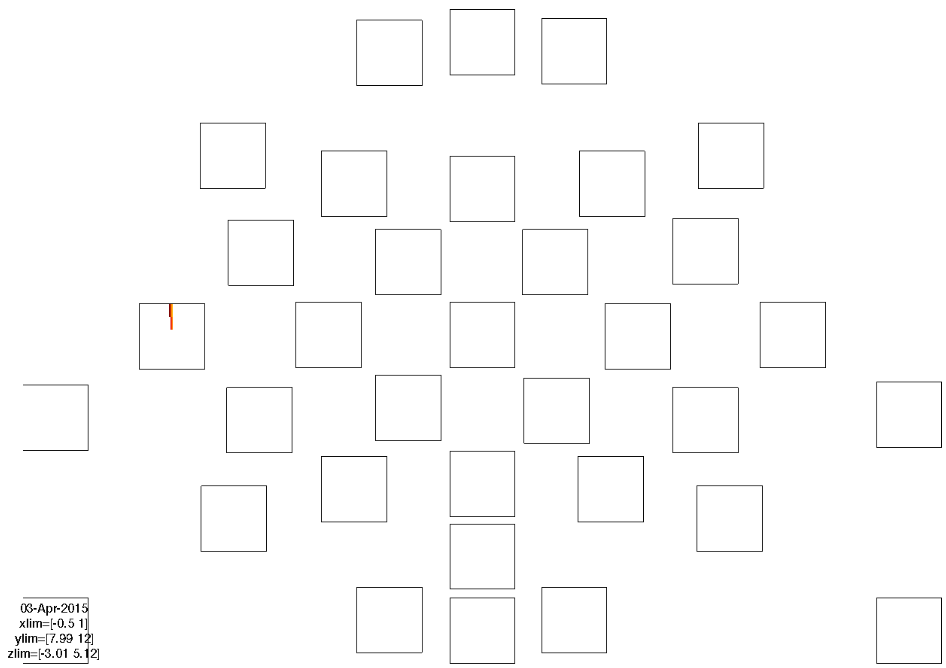


Figure 2.77: PP, long-distance dependency vs. DO, Control: Alpha band (8-12Hz) masked stats TFR, significant channels

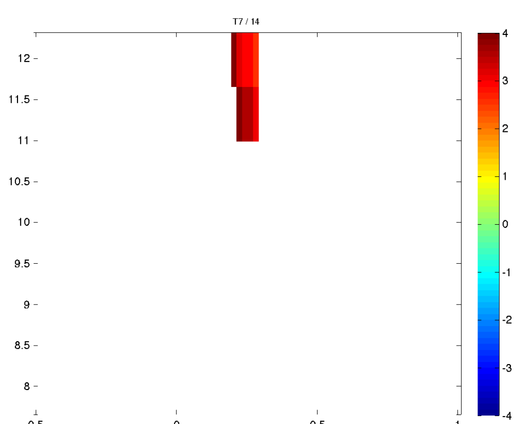


Figure 2.78: PP, long-distance dependency vs. DO, Control: Lower Beta band (13-20Hz) masked stats TFR

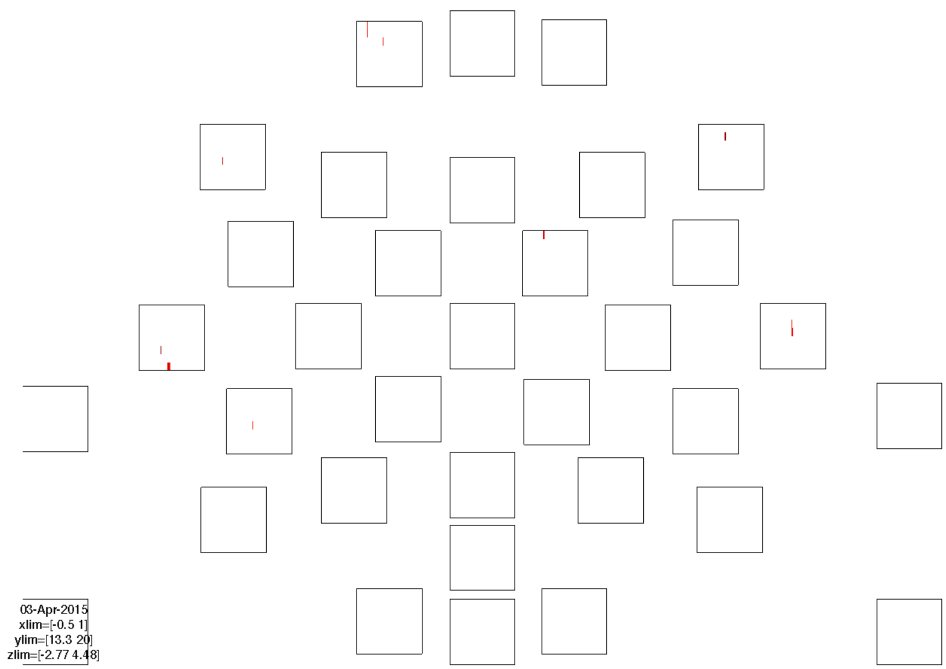


Figure 2.79: PP, long-distance dependency vs. DO, Control: Lower Beta band (13-20Hz) masked stats TFR, significant channels

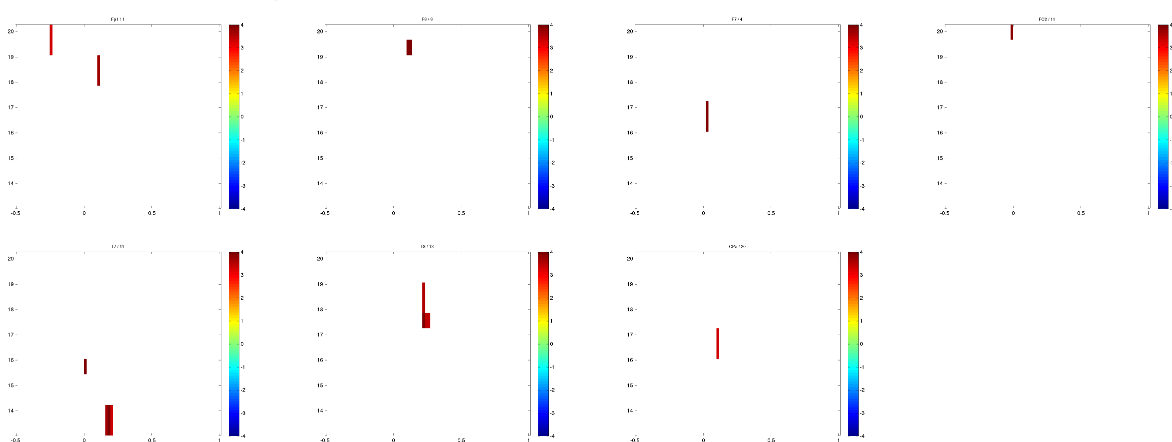


Figure 2.80: PP, long-distance dependency vs. DO, Control: Upper Beta band (21-30Hz) masked stats TFR

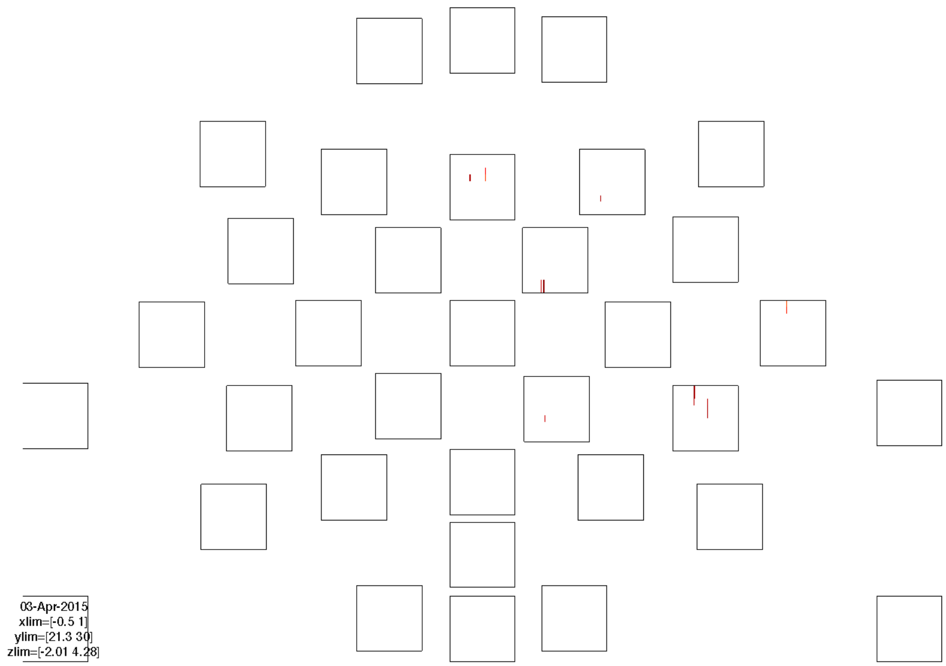


Figure 2.81: PP, long-distance dependency vs. DO, Control: Upper Beta band (21-30Hz) masked stats TFR, significant channels

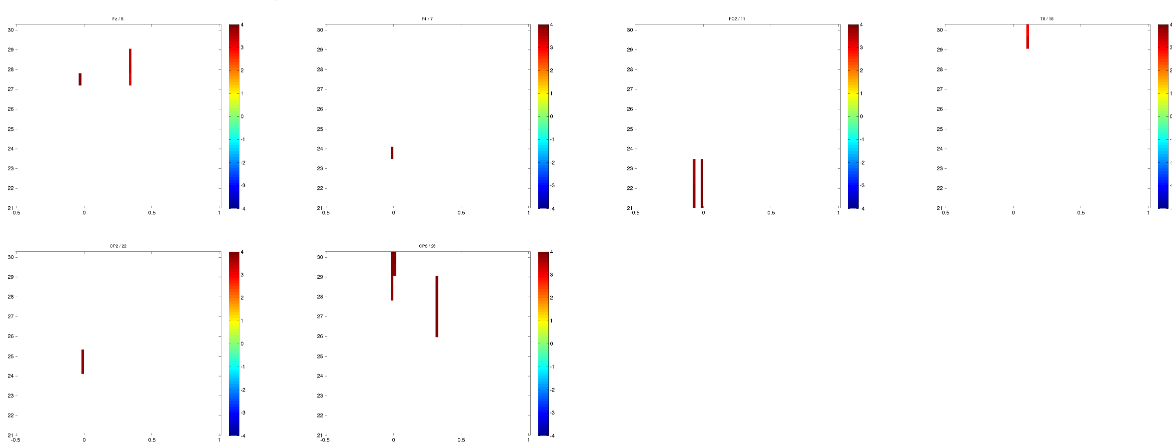


Figure 2.82: PP, long-distance dependency vs. DO, Control: Gamma band (31-40Hz) masked stats TFR

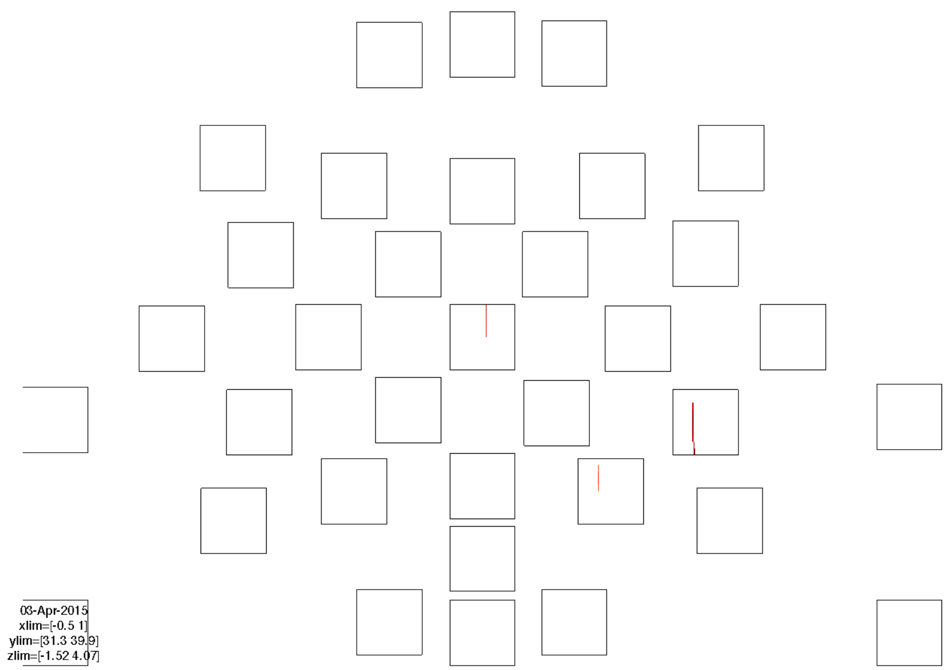
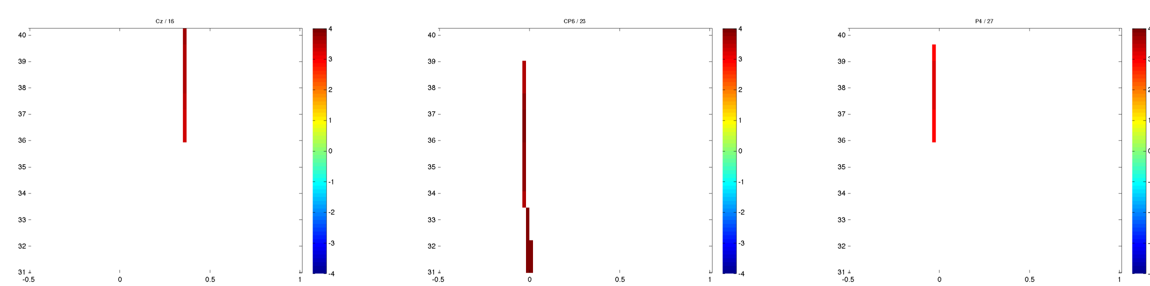


Figure 2.83: PP, long-distance dependency vs. DO, Control: Gamma band (31-40Hz) masked stats TFR, significant channels



long-distance dependency vs. short-distance dependency: first word of dependency vs. gap resolution

WHS The cameraman knew *who* *would* honor the soldiers before *the* fireworks.
WHO The cameraman knew *who* *the* former mayor would honor *before* the fireworks.

ERPs

Comparing the article *the* of the long-distance dependency to the modal (e.g., *could*) of the short-distance dependency condition, there is a positive going deflection following the article of the long-distance dependency, which is visible in 100ms time slices from 100 to 300ms and again at 900ms, and a negative going deflection following the long-distance dependency which is visible in 100ms time slices from 500-700ms. According to the t_{max} permutation tests, this positivity is significant in left posterior channel 'P7' at ∼675ms (Fig. 2.86).

Figure 2.84: *the*, long-distance dependency vs. Modal, short-distance dependency: ERPs

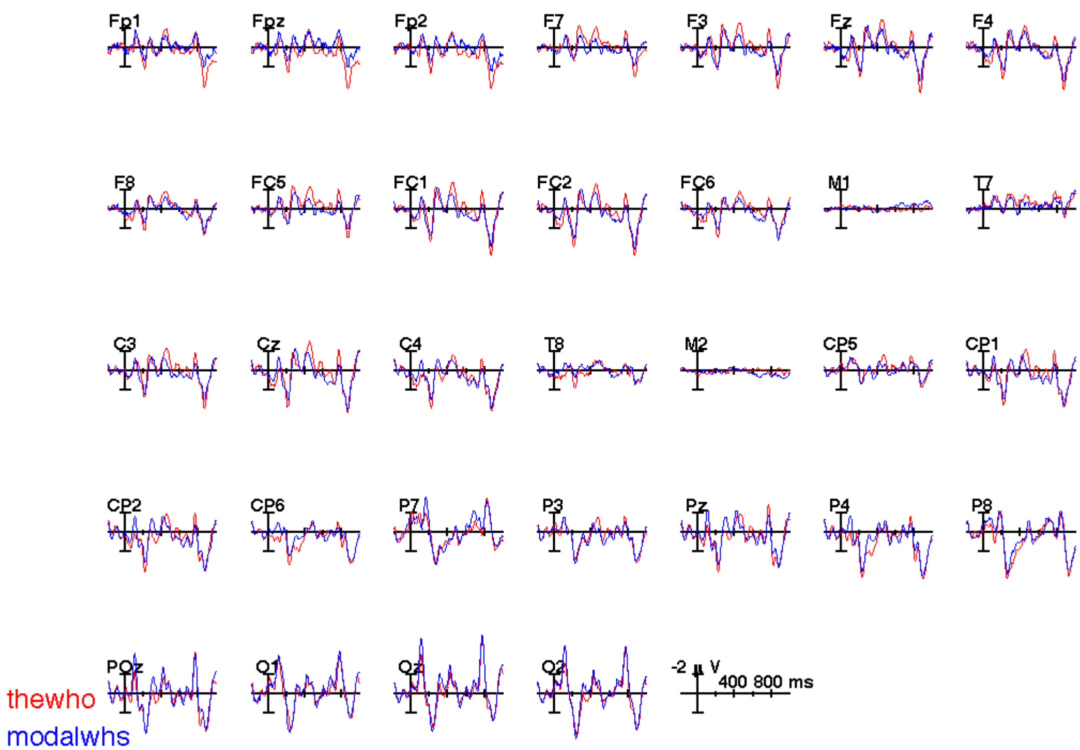
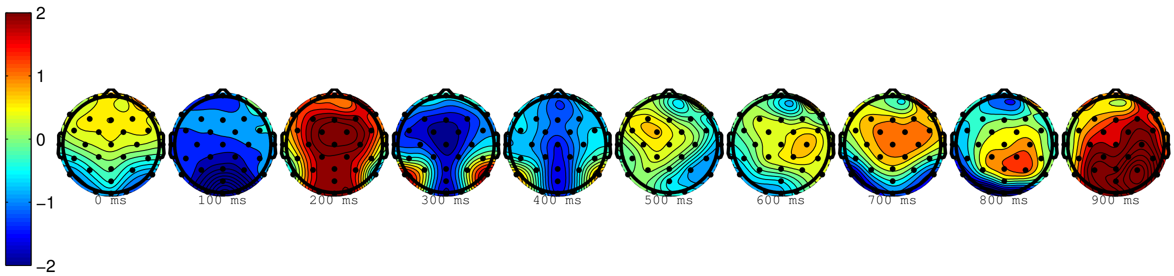
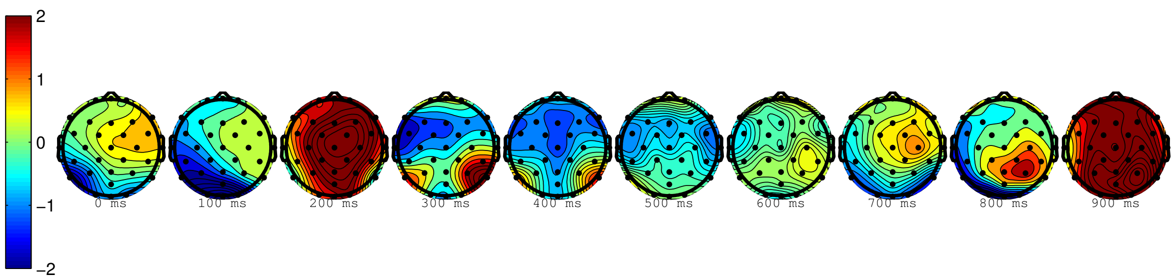


Figure 2.85: *the*, Long-distance vs. Modal, short-distance dependency: topoplots

Modal, short-distance dependency



the, long-distance dependency



Difference plots

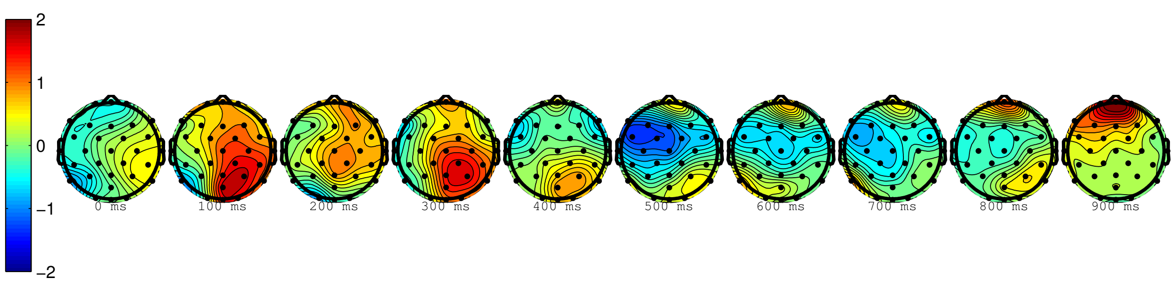


Figure 2.86: *the*, Long-distance vs. Modal, short-distance dependency: t_{max} tests

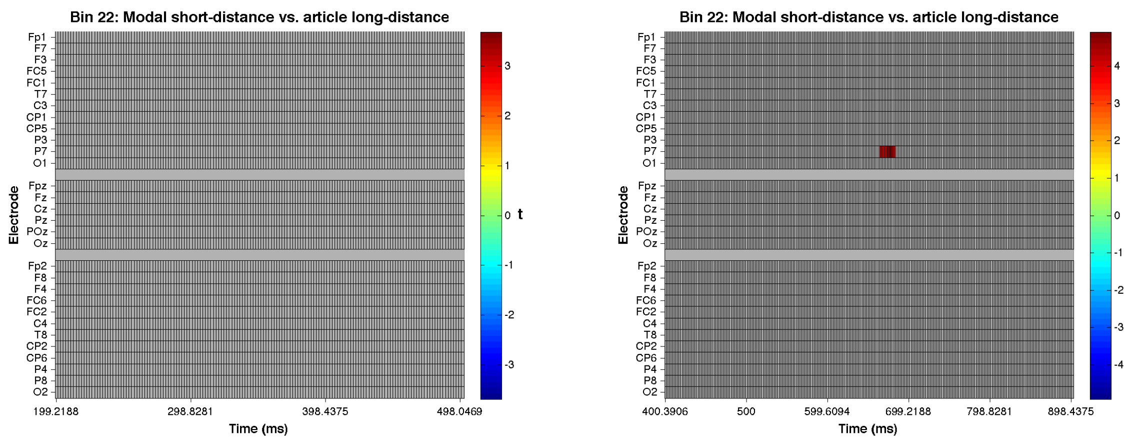
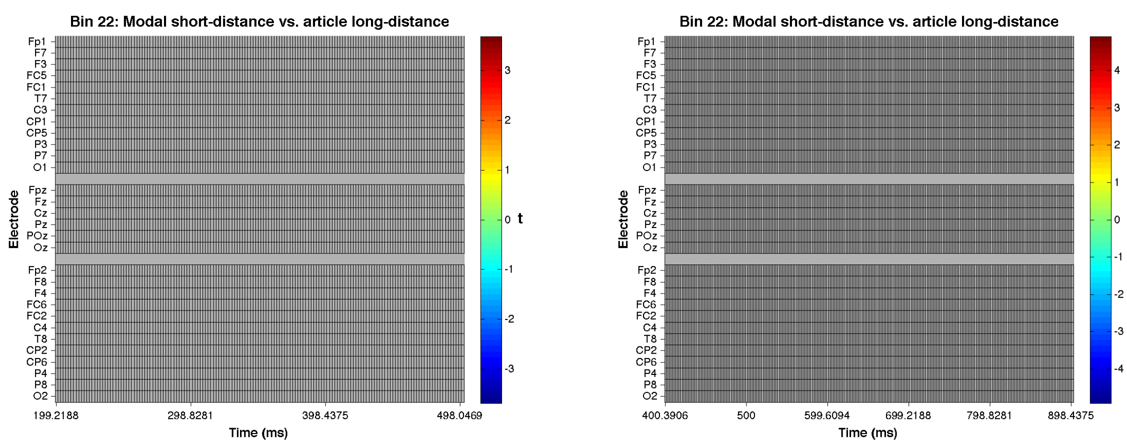


Figure 2.87: *the*, Long-distance vs. Modal, short-distance dependency: cluster mass permutation tests



TFRs

Comparing the article *the* of the long-distance dependency to the modal (e.g., *could*) of the short-distance dependency condition, there is a significant decrease in 20-28Hz (Middle, Upper Beta) activity in occipital channels at ∼800ms.

Figure 2.88: First word of long-distance dependency vs. gap resolution in short-distance dependency: TFR

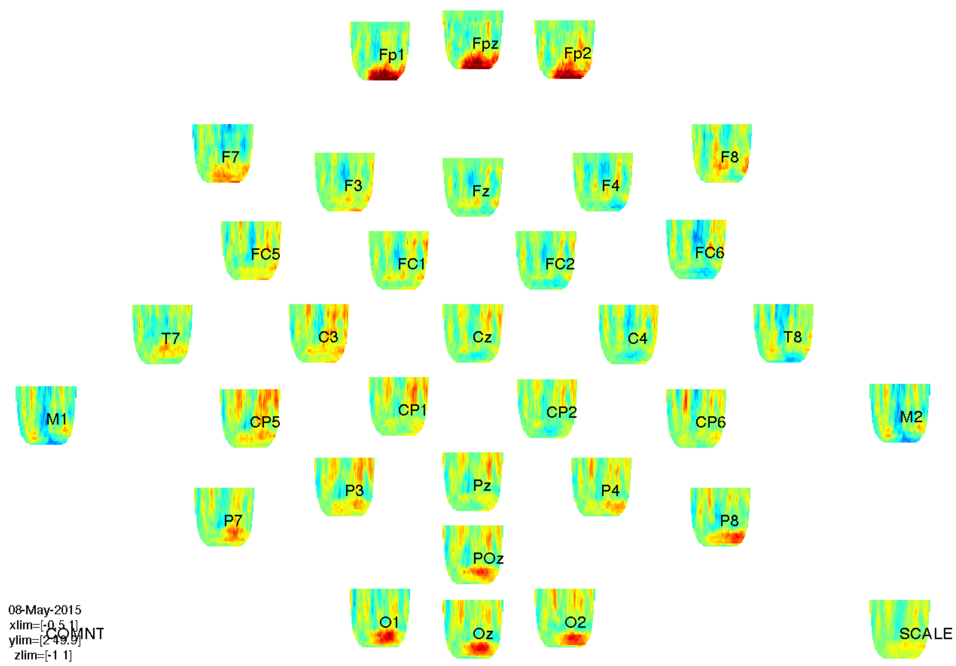


Figure 2.89: First word of long-distance dependency vs. gap resolution in short-distance dependency: Lower Beta band (13-20Hz) masked stats TFR

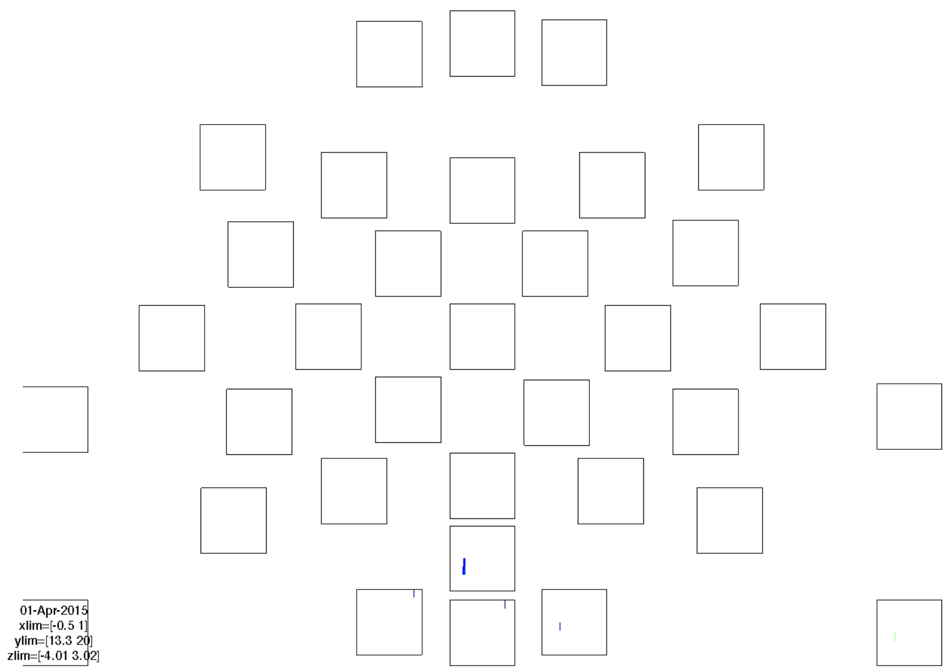


Figure 2.90: First word of long-distance dependency vs. gap resolution in short-distance dependency: Lower Beta band (13-20Hz) masked stats TFR, significant channels

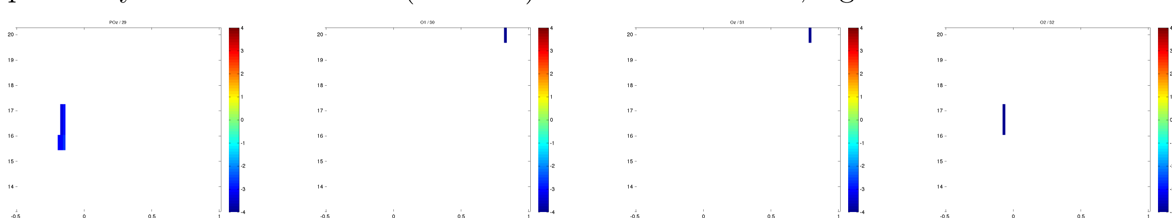


Figure 2.91: First word of long-distance dependency vs. gap resolution in short-distance dependency: Upper Beta band (21-30Hz) masked stats TFR

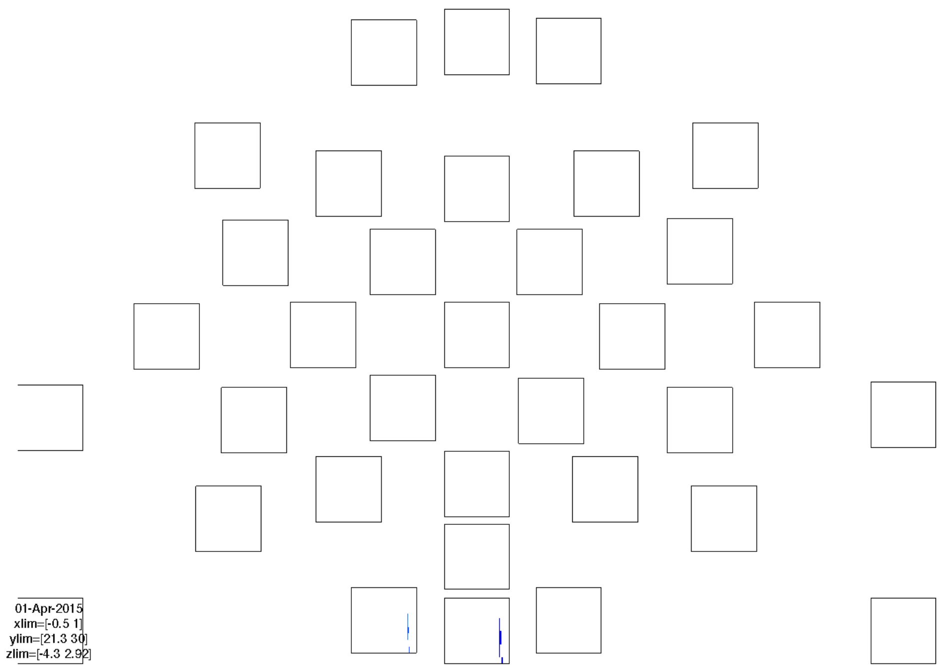
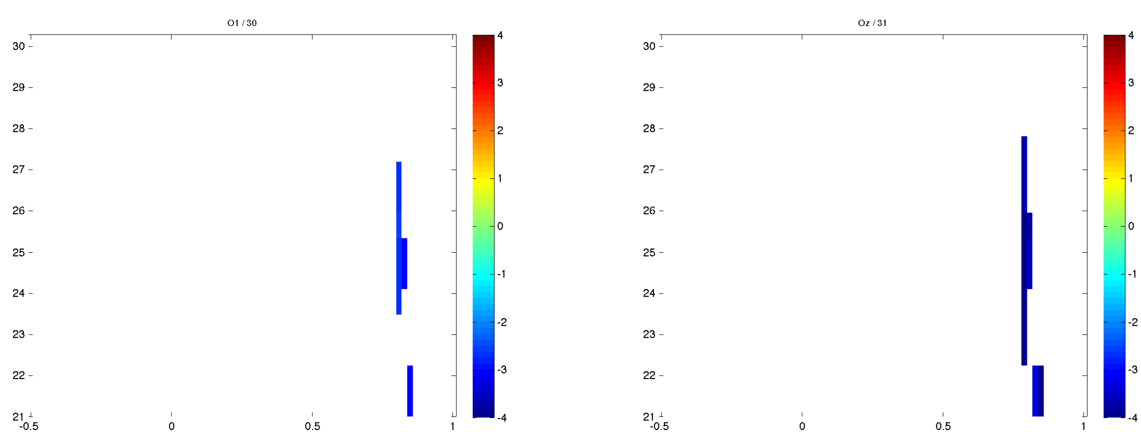


Figure 2.92: First word of long-distance dependency vs. gap resolution in short-distance dependency: Upper Beta band (21-30Hz) masked stats TFR, significant channels



long-distance dependency vs. short-distance dependency: gap resolution vs. DO

WHO The cameraman knew *who* *the* former mayor would honor *before* the fireworks.
WHS The cameraman knew *who* *would* honor the soldiers before *the* fireworks.

ERPs

Finally, comparing the preposition of the adjunct PP of the long-distance dependency condition to the article of the DO of the Control condition, there is a negative going deflection following the long-distance dependency, which is most visible in 100ms time slices from 0-300ms, to a lesser extent between 400-700ms, and again more prominently at 800 and 900ms. Cluster-based permutation tests with cluster α and FWER $\alpha = 0.08$ reveal broad, marginally significant clusters of negative activity in frontal areas, between ~300-400ms (Fig. 2.97).

Figure 2.93: PP, long-distance dependency vs. DO, short-distance dependency: ERPs

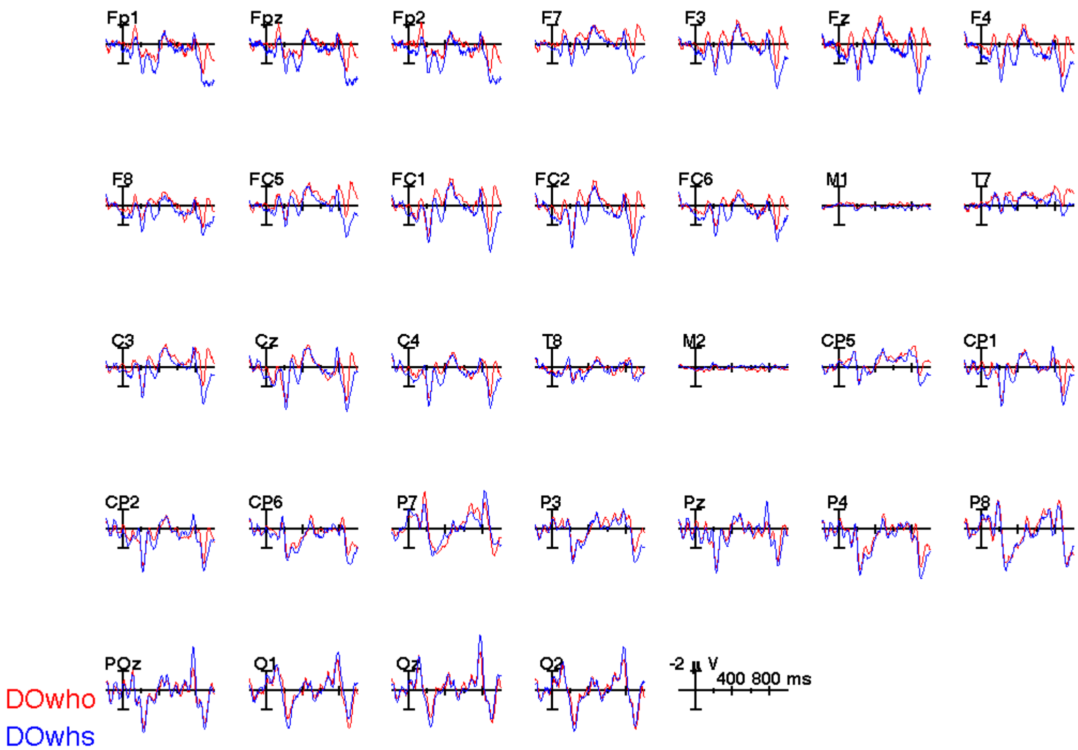
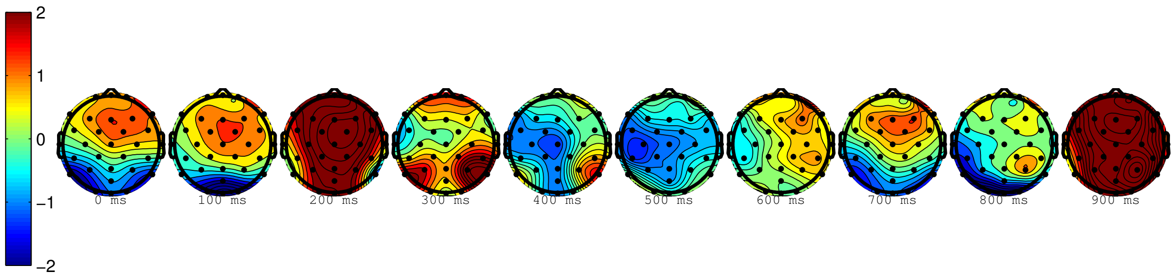
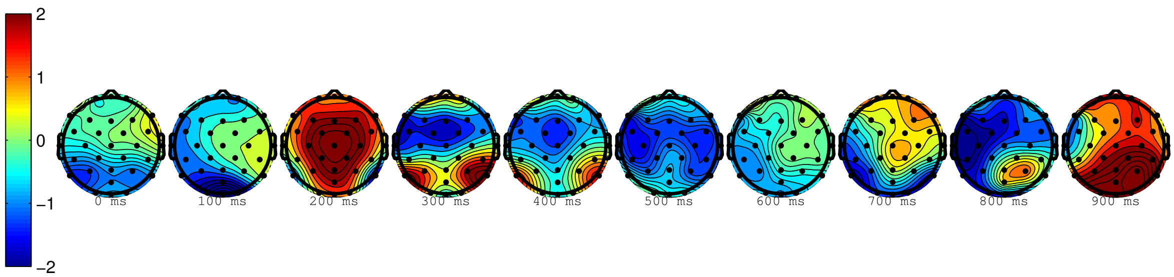


Figure 2.94: PP, Long-distance vs. DO, short-distance dependency: topoplots

DO, short-distance dependency



PP, long-distance dependency



Difference plots

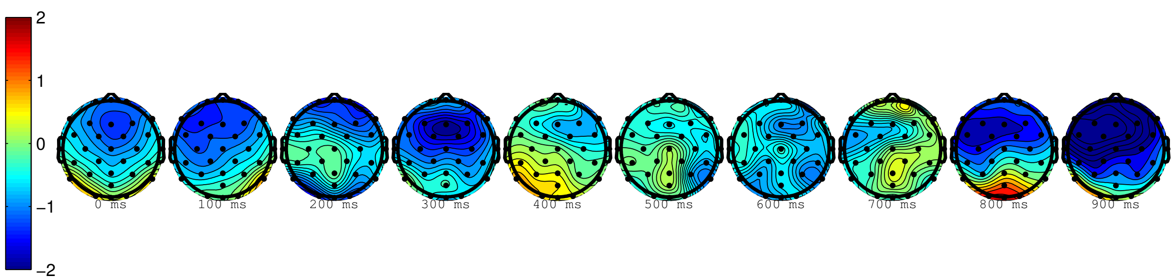


Figure 2.95: PP, Long-distance vs. DO, short-distance dependency: t_{max} tests

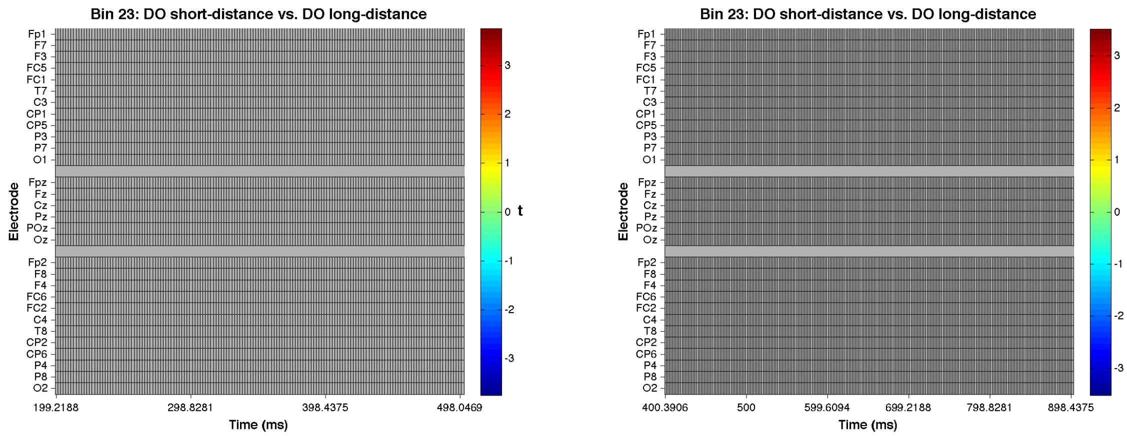


Figure 2.96: PP, Long-distance vs. DO, short-distance dependency: cluster mass permutation tests

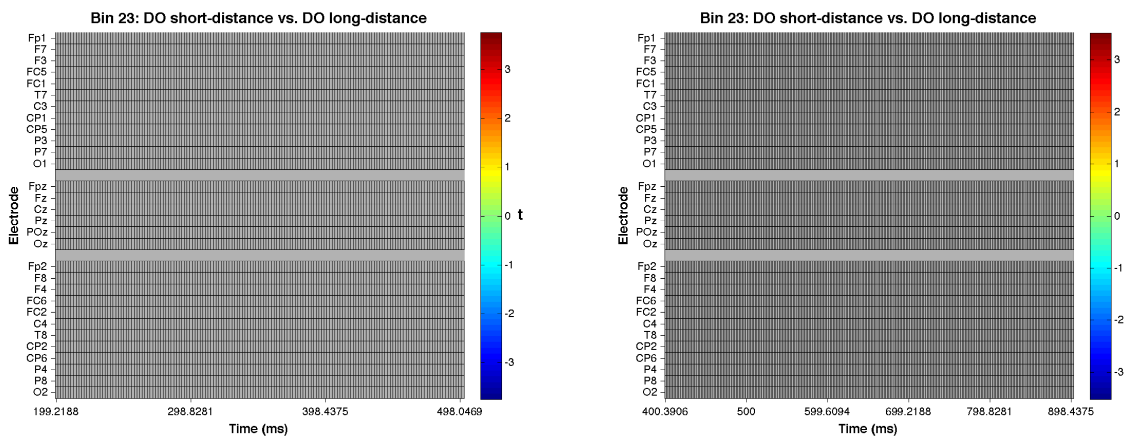
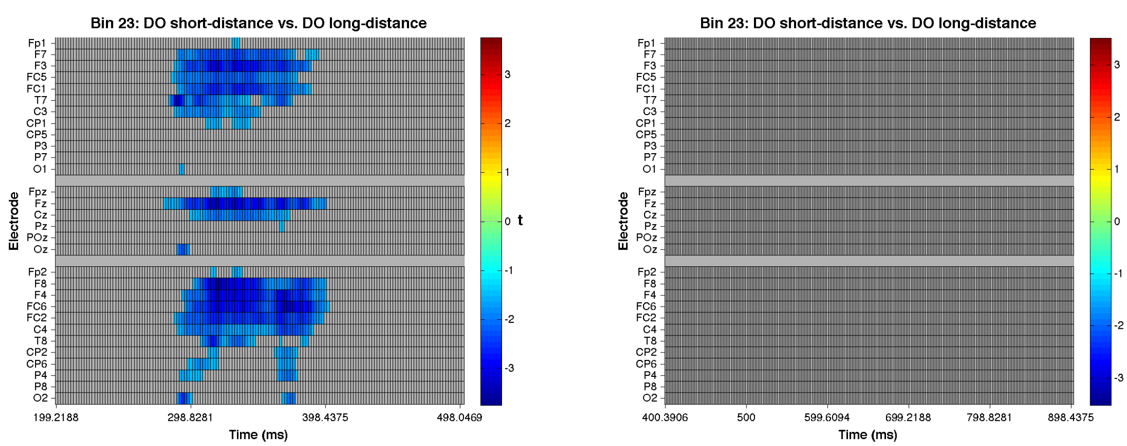


Figure 2.97: PP, Long-distance vs. DO, short-distance dependency: cluster mass permutation tests (cluster alpha=0.8)



TFRs

Comparing the preposition of the adjunct PP of the long-distance dependency condition to the article of the DO of the short-distance dependency condition, there is a significant decrease in the range of 9-23Hz activity from ∼200ms before to ∼200ms after the onset of the preposition (*The cameraman knew who the former mayor would honor* <u>*before*</u> *the fireworks.*), in left anterior and broad posterior areas. There is also an increase in 4-6Hz in left anterior areas, from ∼0-400ms, followed by a significant decrease in 5-6Hz in occipital areas (channel 'Oz') at ∼500ms.

Overall, comparing the preposition of the adjunct PP of the long-distance dependency condition to the article of the DO of the Control condition there is a significant decrease in Alpha and Beta activity in left anterior and posterior areas broadly from ∼200ms before to ∼200ms after the onset of the critical word. There is also a left anterior increase in Theta band activity from ∼0-400ms, followed by a decrease in Theta band activity in occipital areas at ∼500ms.

Figure 2.98: Gap resolution in long-distance dependency vs. DO of short-distance dependency: TFR

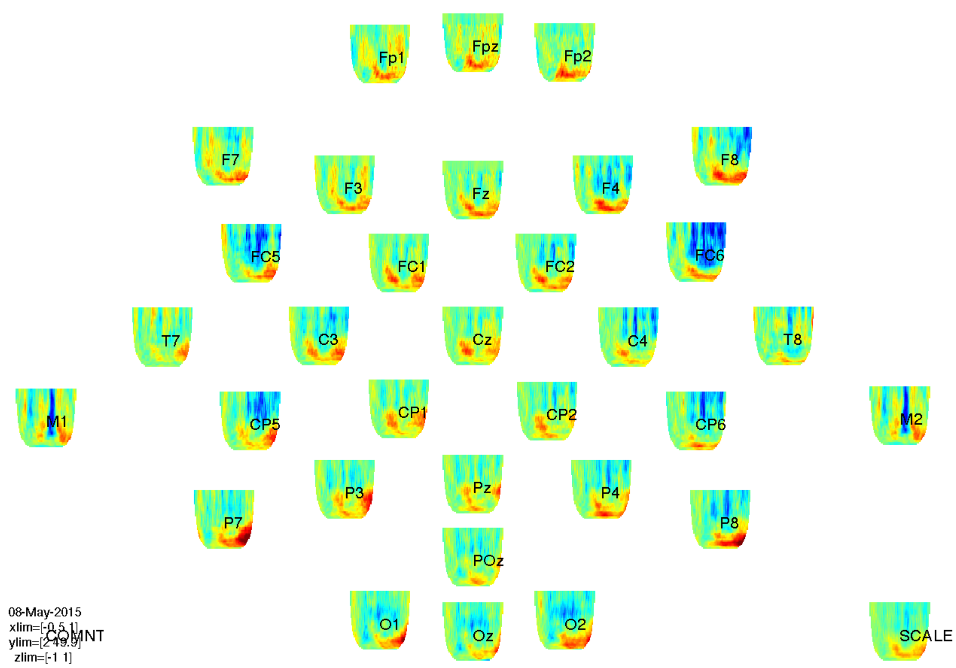


Figure 2.99: Gap resolution in long-distance dependency vs. DO of short-distance dependency: Theta band (4-7Hz) masked stats TFR

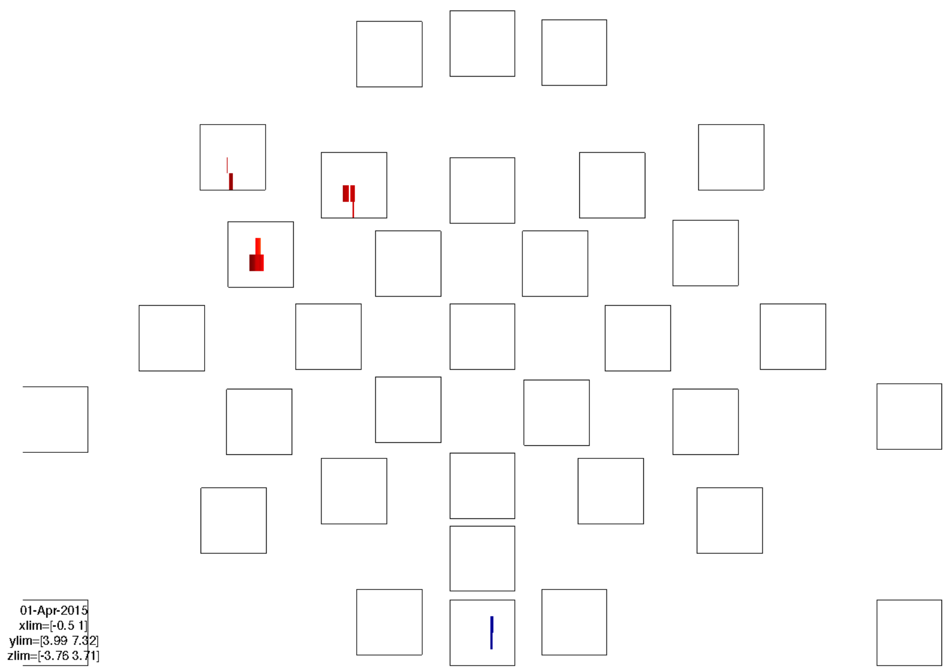


Figure 2.100: Gap resolution in long-distance dependency vs. DO of short-distance dependency: Theta band (4-7Hz) masked stats TFR, significant channels

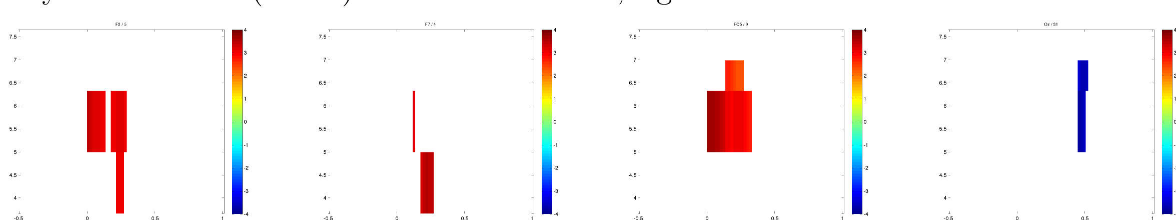


Figure 2.101: Gap resolution in long-distance dependency vs. DO of short-distance dependency: Alpha band (8-12Hz) masked stats TFR

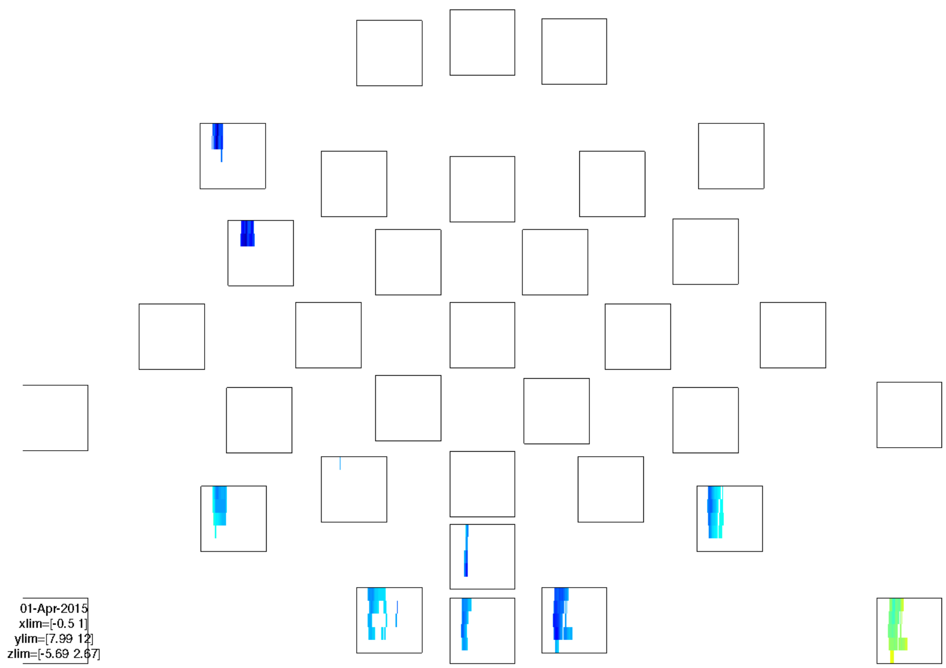


Figure 2.102: Gap resolution in long-distance dependency vs. DO of short-distance dependency: Alpha band (8-12Hz) masked stats TFR, significant channels

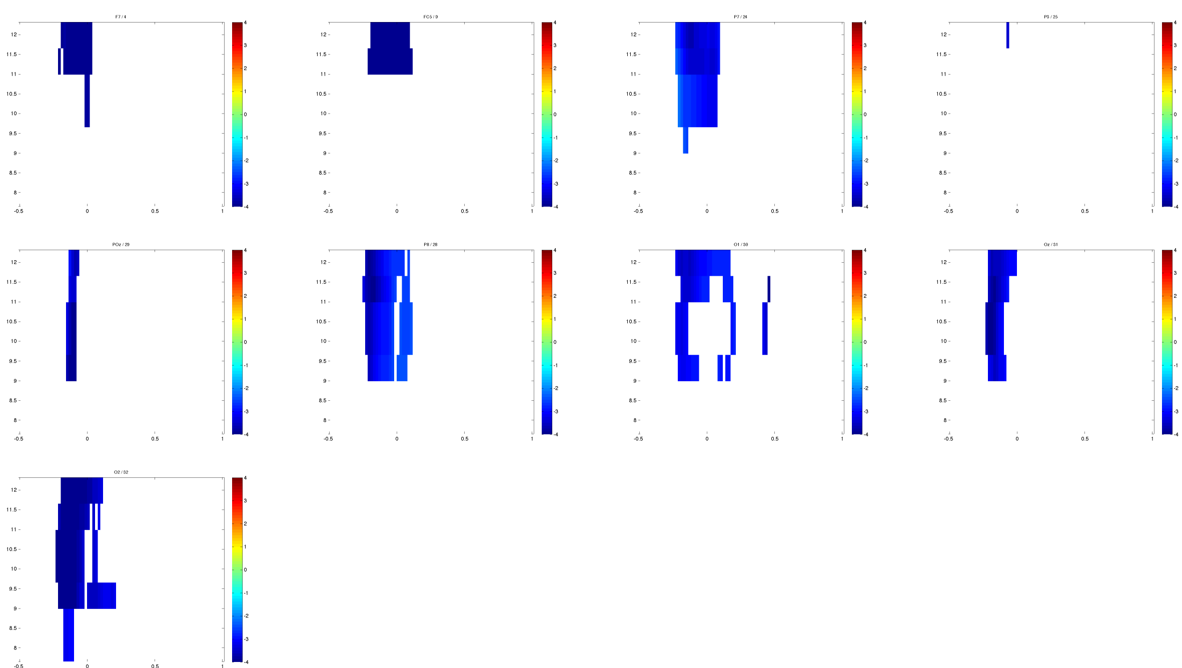


Figure 2.103: Gap resolution in long-distance dependency vs. DO of short-distance dependency: Lower Beta band (13-20Hz) masked stats TFR

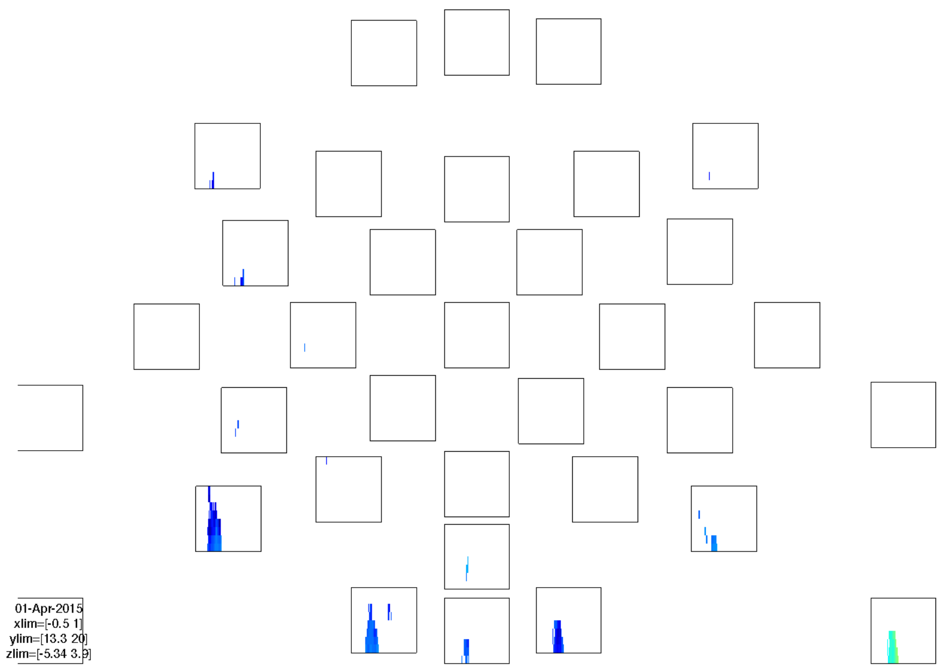


Figure 2.104: Gap resolution in long-distance dependency vs. DO of short-distance dependency: Lower Beta band (13-20Hz) masked stats TFR, significant channels

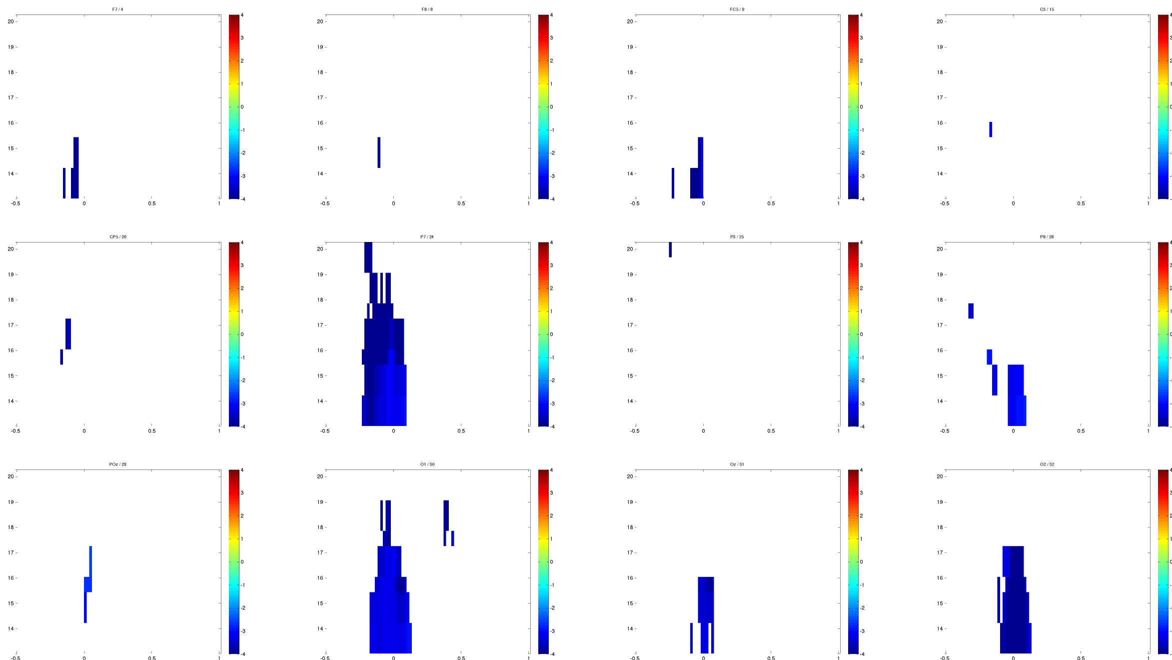


Figure 2.105: Gap resolution in long-distance dependency vs. DO of short-distance dependency: Upper Beta band (21-30Hz) masked stats TFR

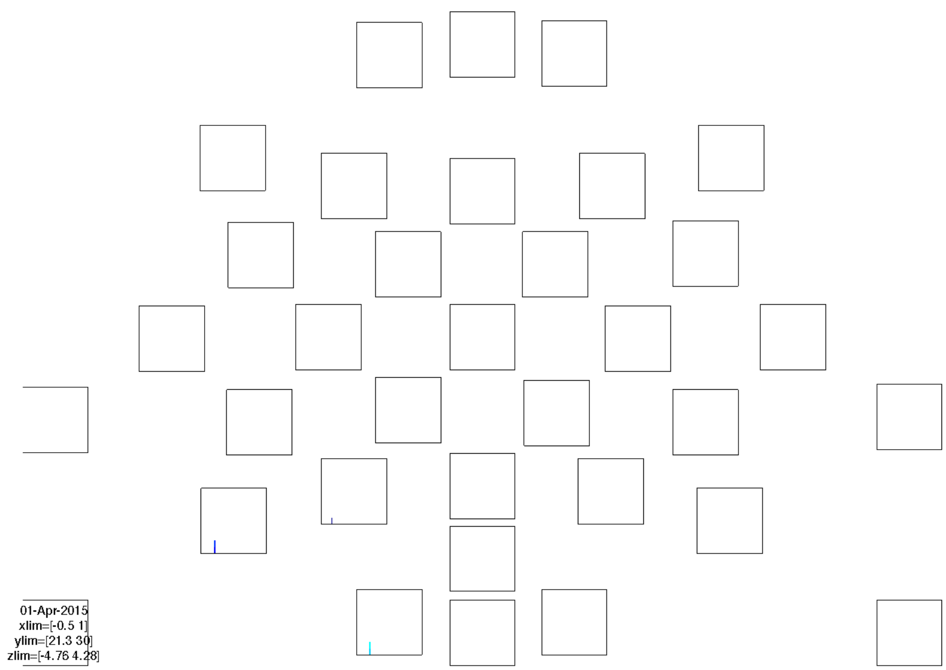
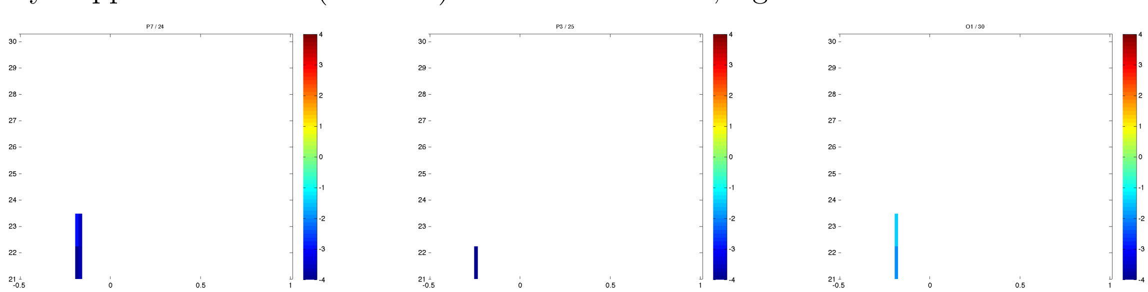


Figure 2.106: Gap resolution in long-distance dependency vs. DO of short-distance dependency: Upper Beta band (21-30Hz) masked stats TFR, significant channels



Whether complementizer vs. Control

CONTROL	The cameraman knew *that* *the* former mayor would *honor* *the* soldiers before the fireworks.
WHETHER	The cameraman knew *whether* *the* former mayor would honor *the* soldiers before the fireworks.

ERPs

In a comparison of the *wh*-complementizer *whether* vs. the complementizer *that*, there is a broad negative going deflection at 300ms, followed by a broad positive going deflection at 500ms. Results of t_{max} permutation tests find significant negative activity in occipital channels bilaterally at ∼300ms, and positive activity in left temporal channel 'T7' at ∼500ms (Fig. 2.109). Cluster-based permutation tests with cluster α and FWER $\alpha = 0.08$ reveal broad, marginally significant clusters of (slightly left-biased) positive activity, between ∼400-900ms (Fig. 2.111).

Figure 2.107: Whether vs. *that*, Control: ERPs

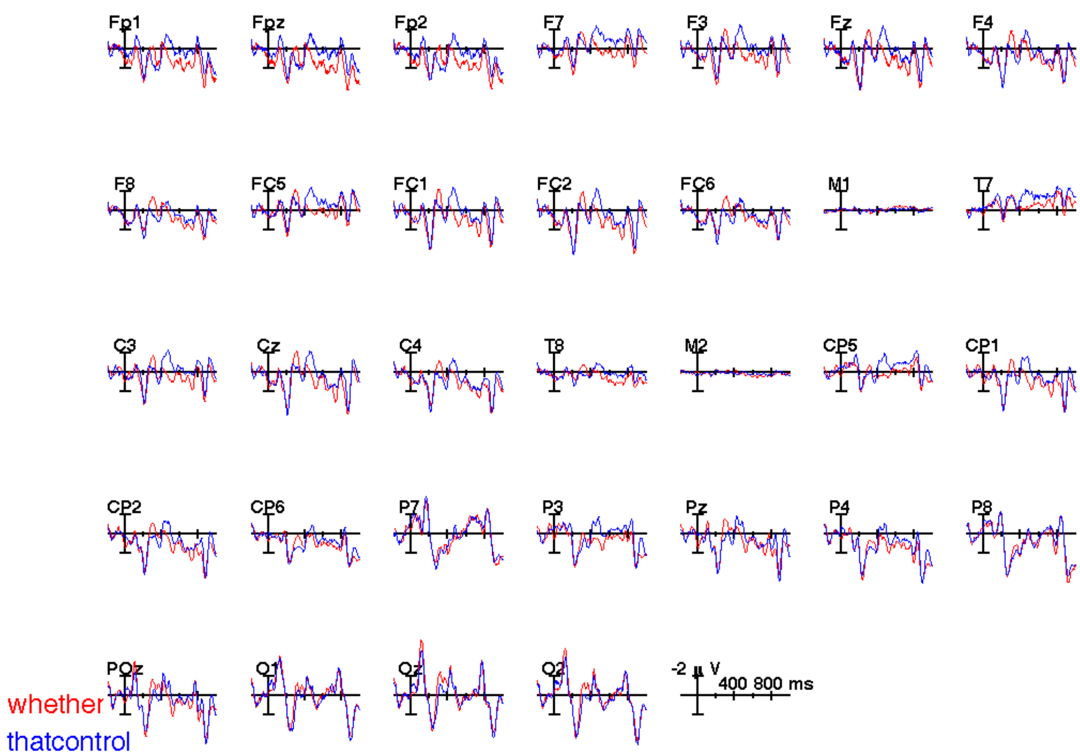
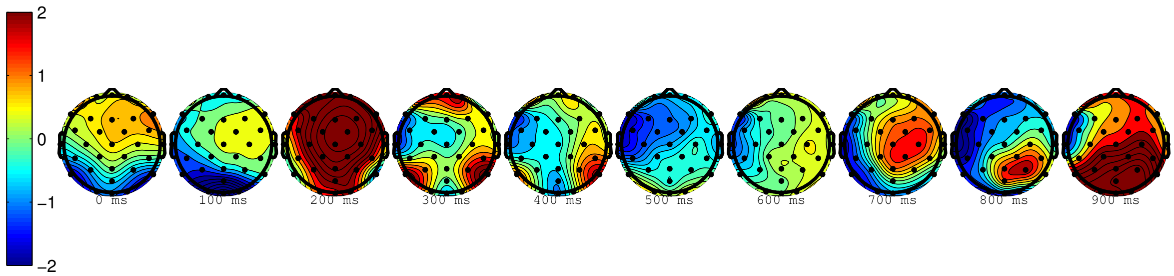
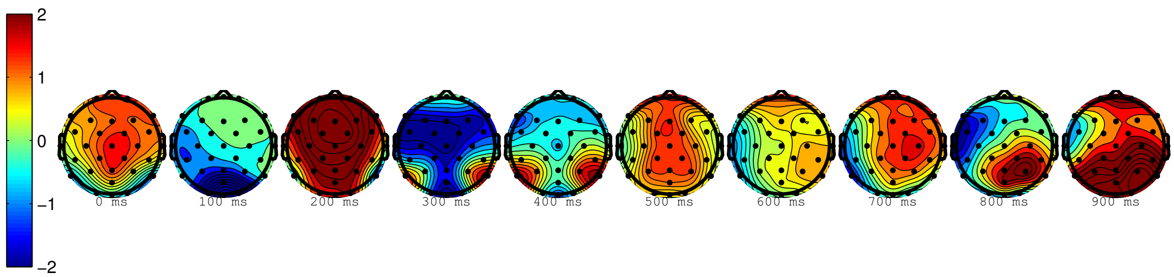


Figure 2.108: Whether vs. *that*, Control: topoplots

that Control



Whether



Difference plots

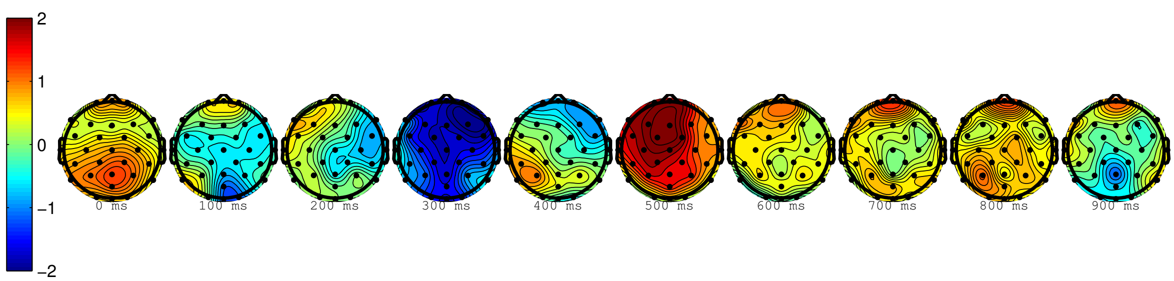


Figure 2.109: Whether vs. *that*, Control: t_{max} permutation tests

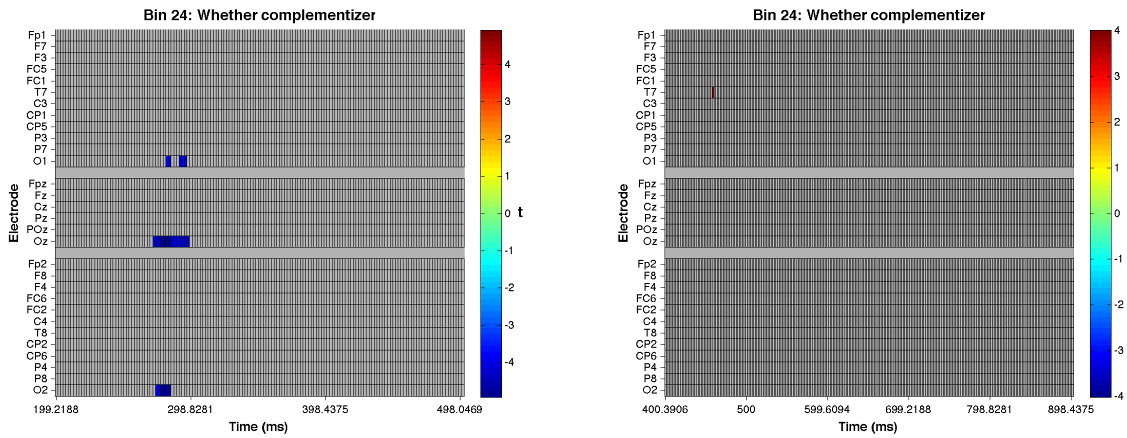


Figure 2.110: Whether vs. *that*, Control: cluster mass permutation tests

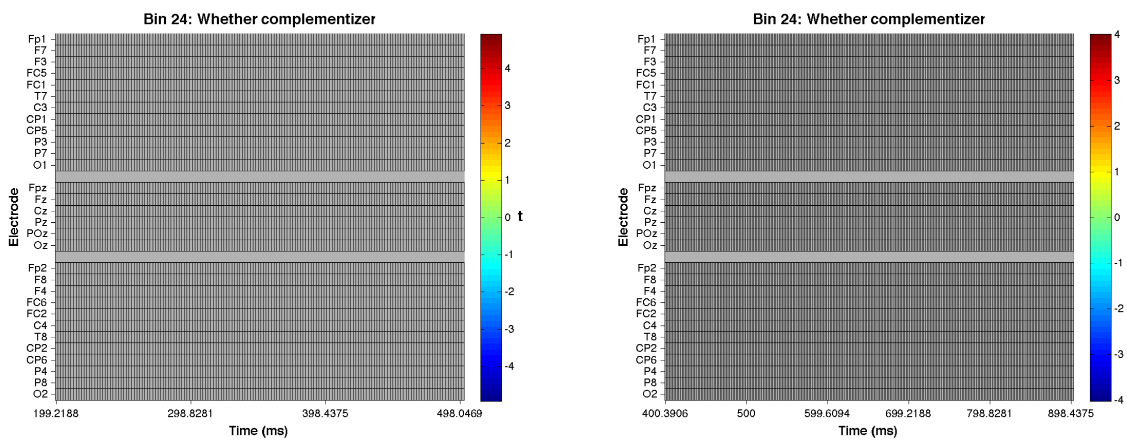
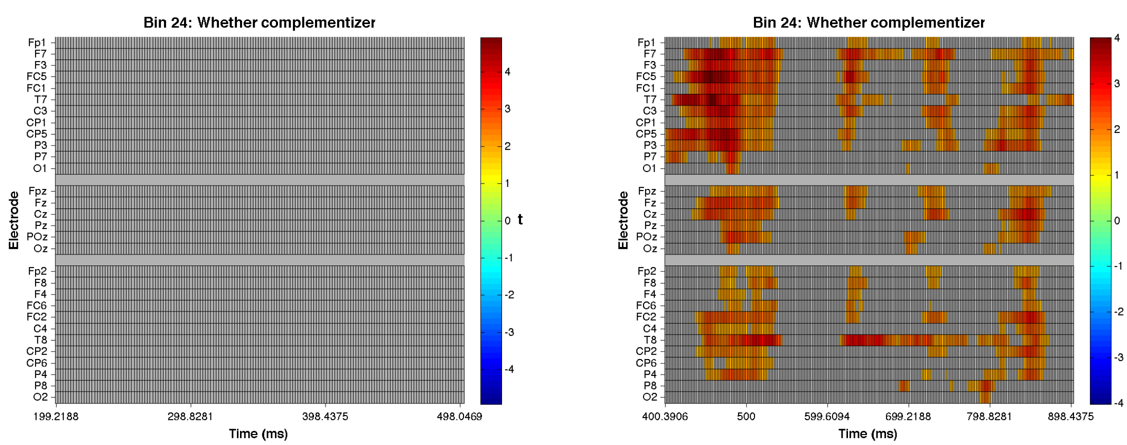


Figure 2.111: Whether vs. *that*, Control: cluster mass permutation tests (cluster alpha=0.8)



TFRs

In a comparison of the *wh*-complementizer *whether* vs. the complementizer *that*, there is a significant decrease in 11-12Hz activity in left anterior from ∼500ms to ∼550ms. During this same time window there are decreases in the 13-19Hz range in left anterior areas, and a decrease in 24-25Hz in right occipito-parietal areas (channel 'P8').

Overall, in a comparison of the *wh*-complementizer *whether* vs. the complementizer *that*, there are significant decreases in Alpha and Lower Beta bands in left anterior areas from ∼500ms to ∼550ms, as well as a significant decrease in Upper Beta activity in occipito-parietal channel 'P8.'

Figure 2.112: Whether complementizer vs. that: TFR

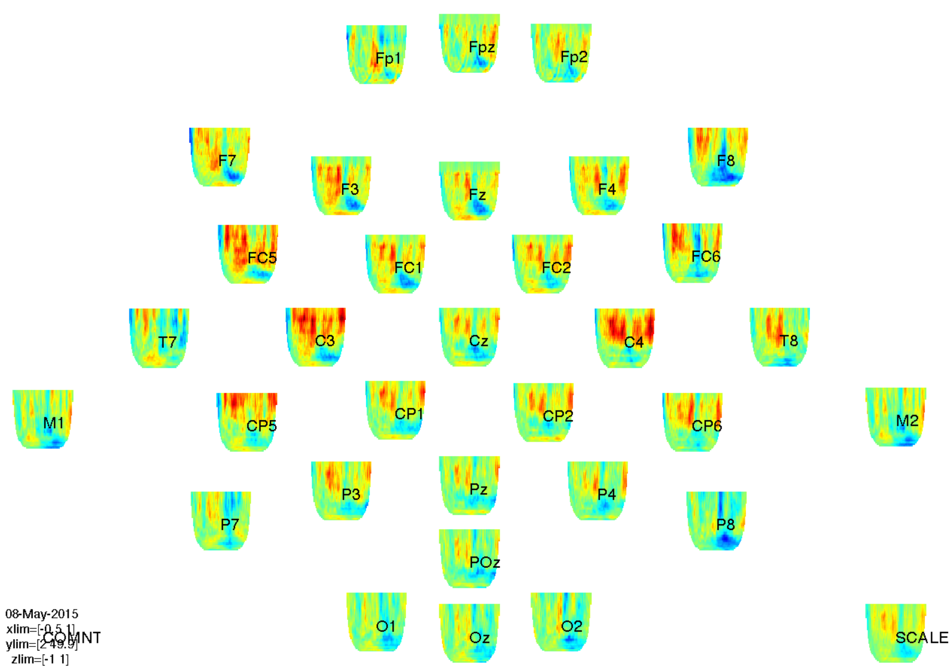


Figure 2.113: Whether complementizer vs. that: Alpha band (8-12Hz) masked stats TFR

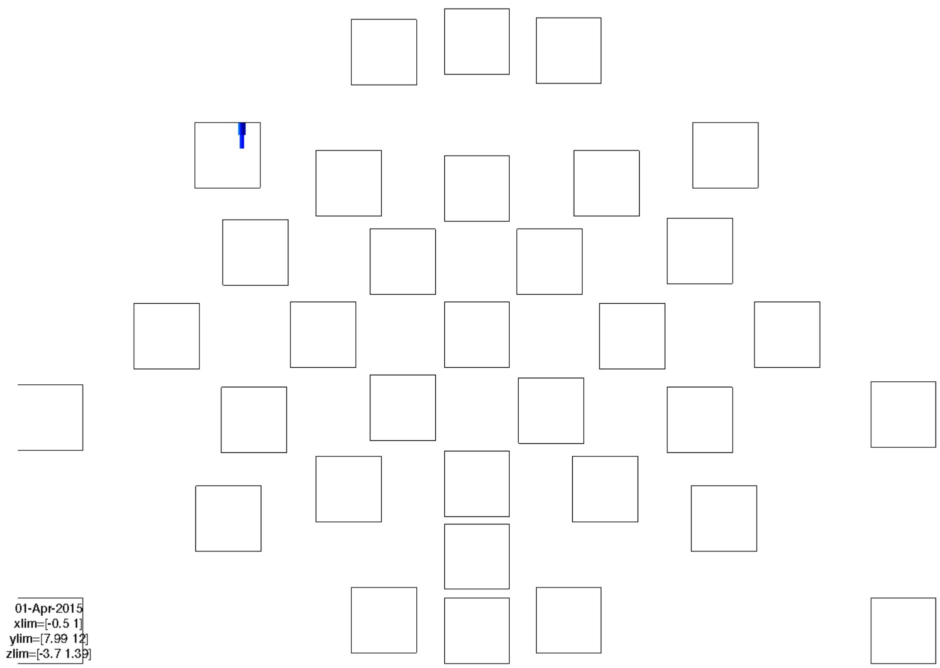


Figure 2.114: Whether complementizer vs. that: Alpha band (8-12Hz) masked stats TFR, significant channels

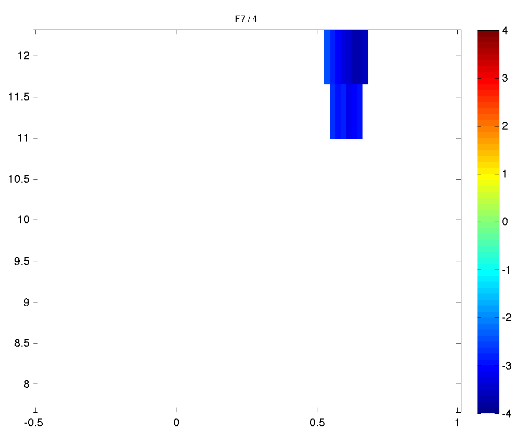


Figure 2.115: Whether complementizer vs. that: Lower Beta band (13-20Hz) masked stats TFR

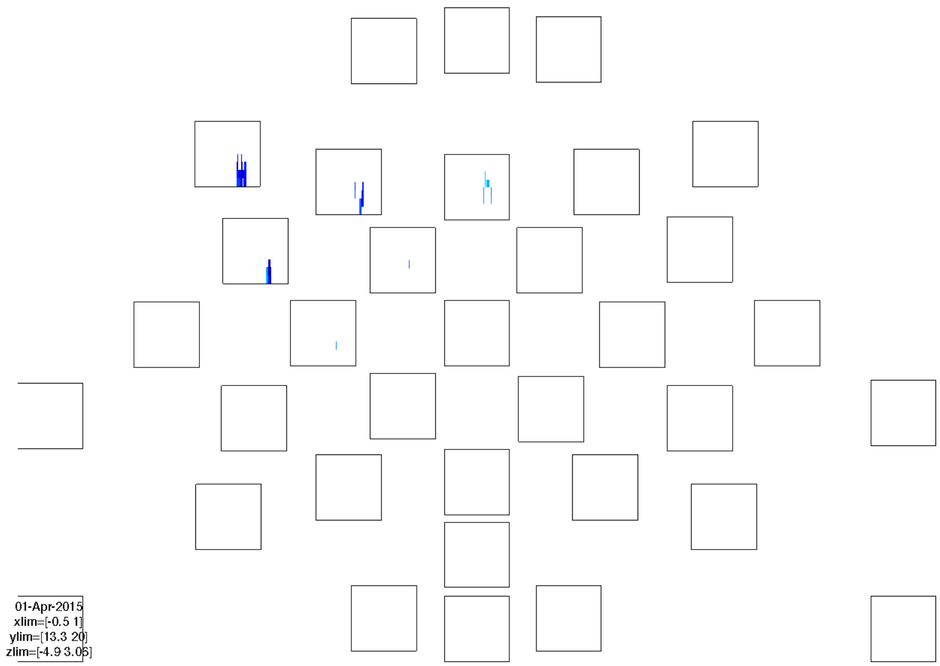


Figure 2.116: Whether complementizer vs. that: Lower Beta band (13-20Hz) masked stats TFR, significant channels

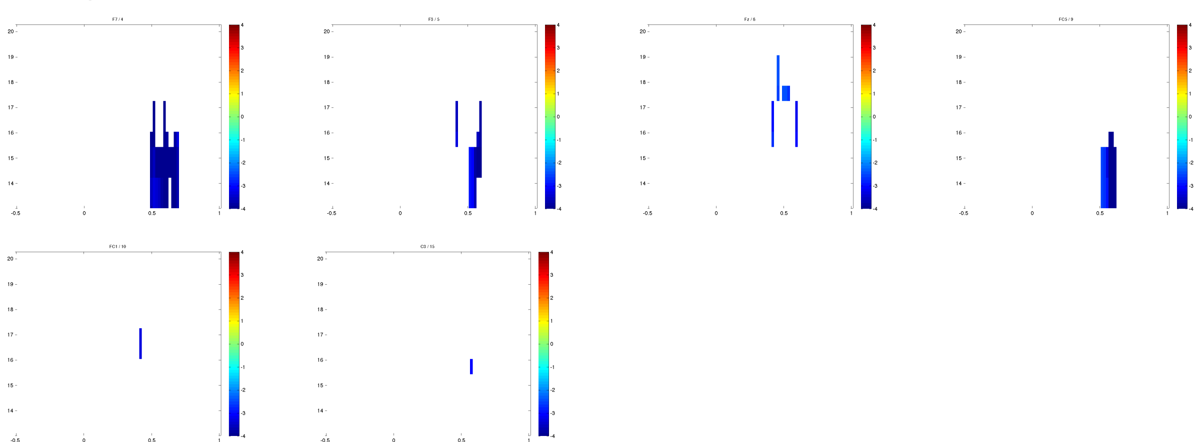


Figure 2.117: Whether complementizer vs. that: Upper Beta band (21-30Hz) masked stats TFR

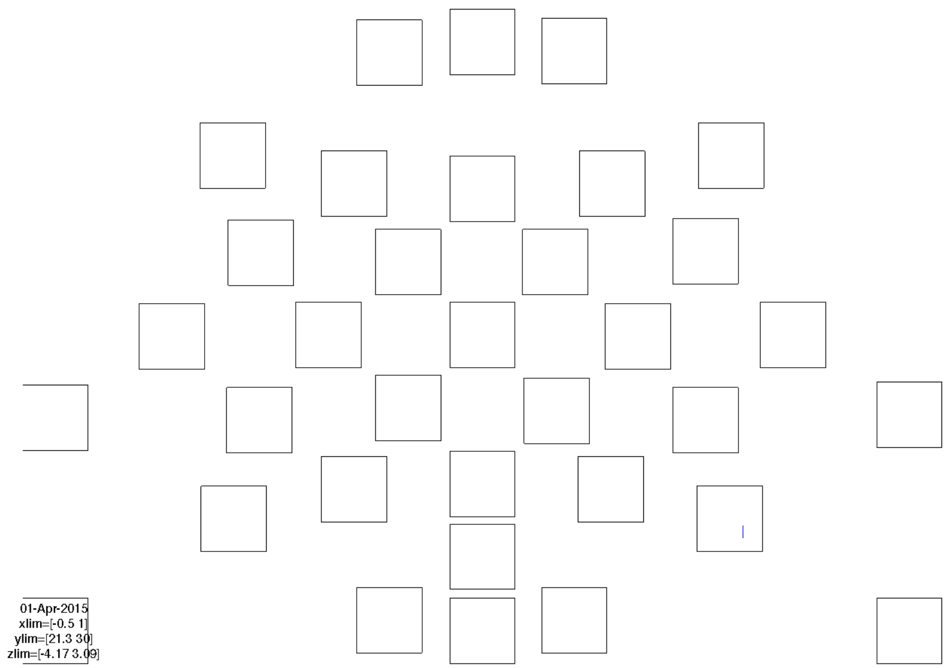
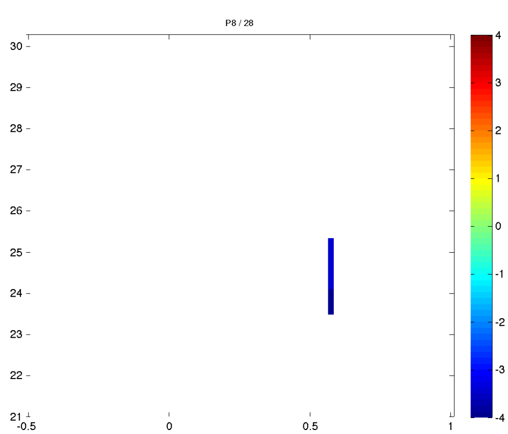


Figure 2.118: Whether complementizer vs. that: Upper Beta band (21-30Hz) masked stats TFR, significant channels



First word after *whether* complementizer vs. first word after control complementizer *that*

CONTROL	The cameraman knew *that* *the* former mayor would *honor* *the* soldiers before the fireworks.
WHETHER	The cameraman knew *whether* *the* former mayor would honor *the* soldiers before the fireworks.

ERPs

In a comparison of the article *the* in the Whether condition vs. control, there is a visible negative going deflection in anterior and later posterior regions broadly, lasting from ∼400-900ms. This difference is not significant at any channel×time point, however, according to t_{max} and cluster-based permutation tests.

Figure 2.119: *the*, Whether vs. *the*, Control: ERPs

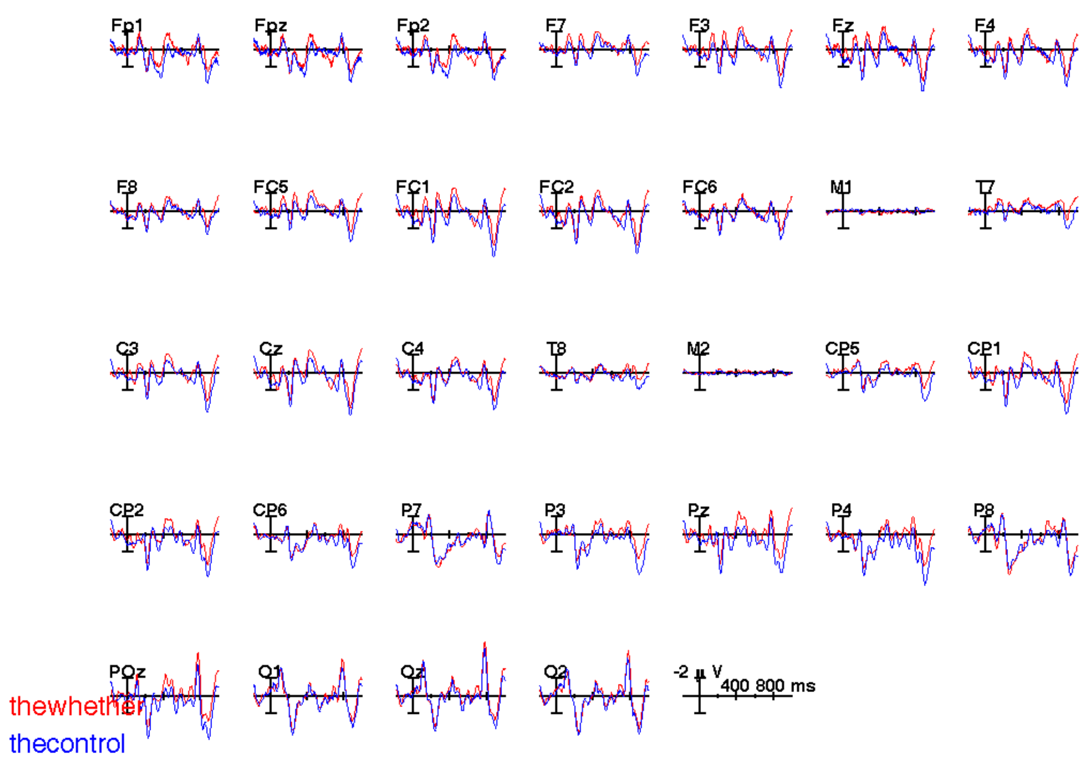
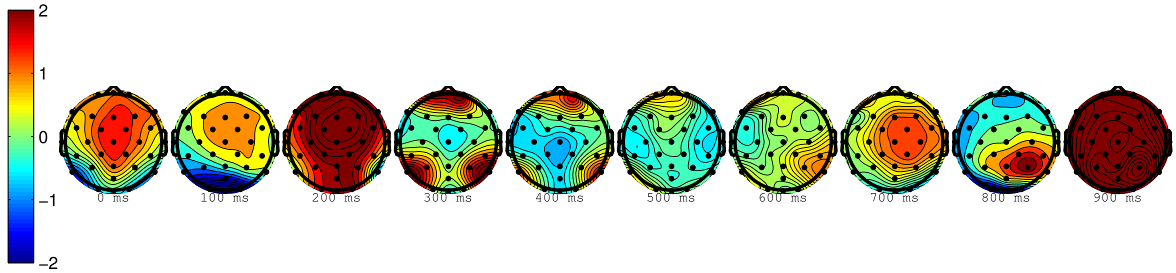
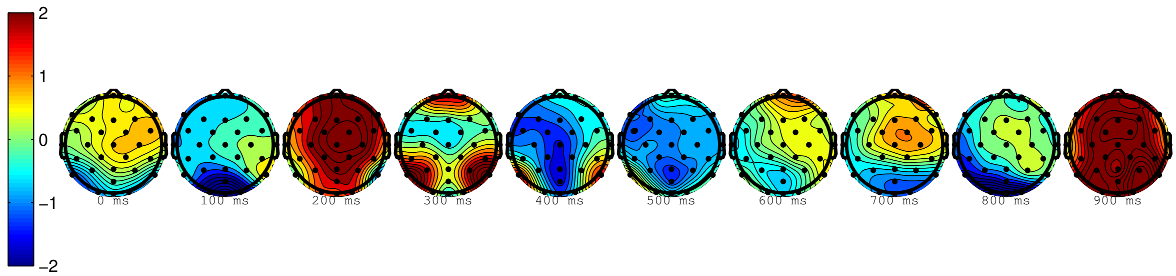


Figure 2.120: *the*, Whether vs. *the*, Control: topoplots

the Control



the, Whether



Difference plots

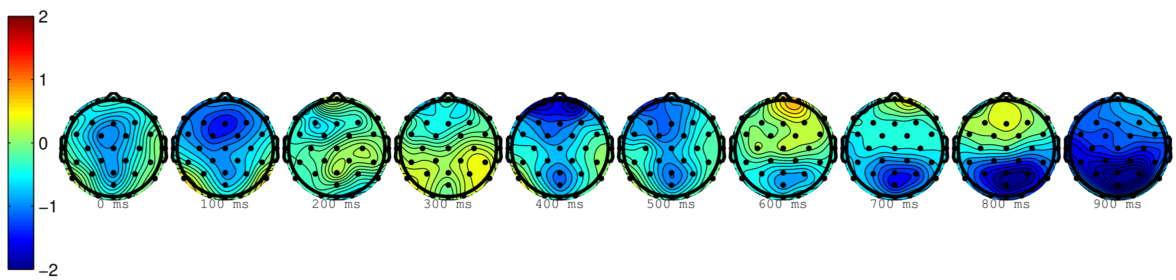


Figure 2.121: *the*, Whether vs. *the*, Control: t_{max} permutation tests

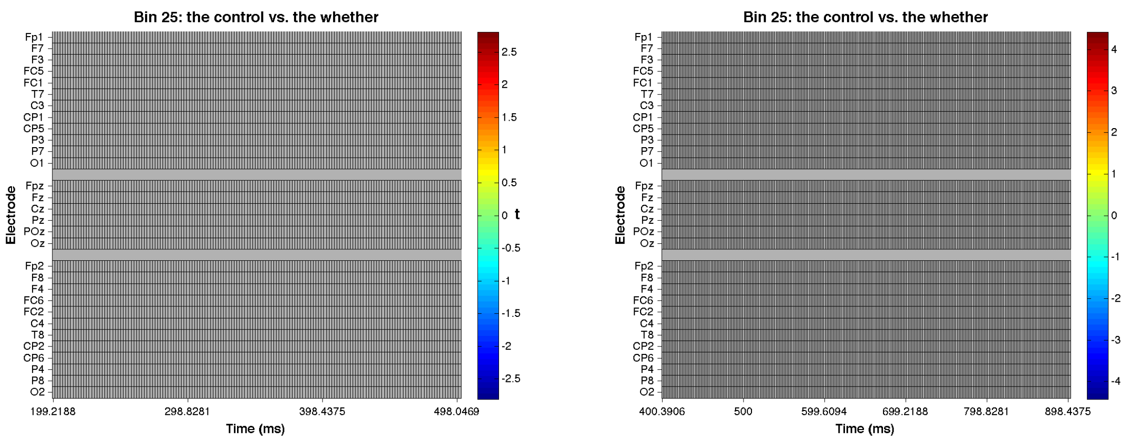
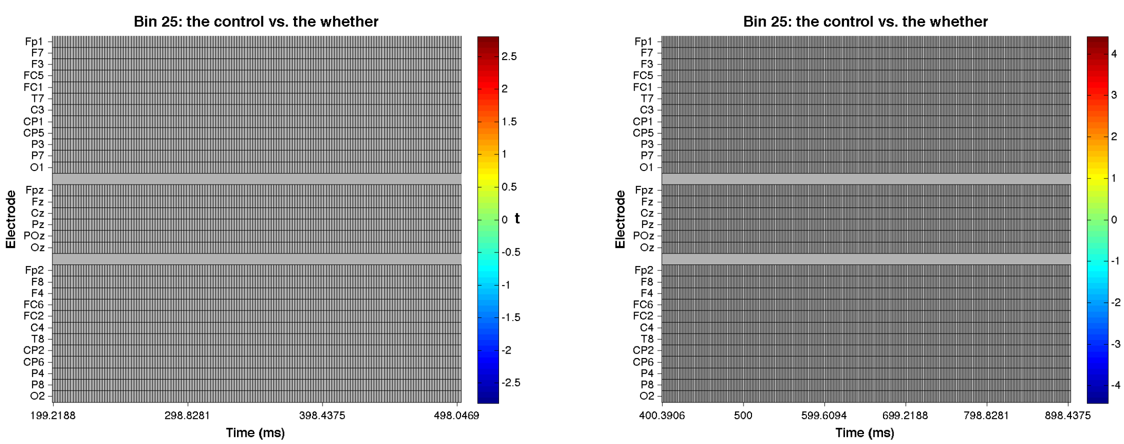


Figure 2.122: *the*, Whether vs. *the*, Control: cluster mass permutation tests



TFRs

In a comparison of the article *the* in the Whether condition vs. the article *the* in the Control condition, there is a significant relative decrease in 10-12Hz activity immediately prior to/at the onset of the critical word, in left anterior areas. There are similar decreases in 13-19Hz in the range of ∼-200ms, to the critical word onset, and there is a significant decrease of 24-25Hz activity in right occipito-parietal areas (channel 'P8') ∼50ms prior to the onset of the critical word.

Overall, in a comparison of the article *the* in the Whether condition vs. the article *the* in the Control condition, there are significant decreases in Alpha and Lower Beta activity in left anterior areas, in the range of ∼200ms prior to the critical word onset, and there is a significant decrease in Upper Beta activity in right occipito-partietal channel 'P8' at ∼50ms prior to the critical word.

Figure 2.123: First word after *whether* complementizer vs. Control: TFR

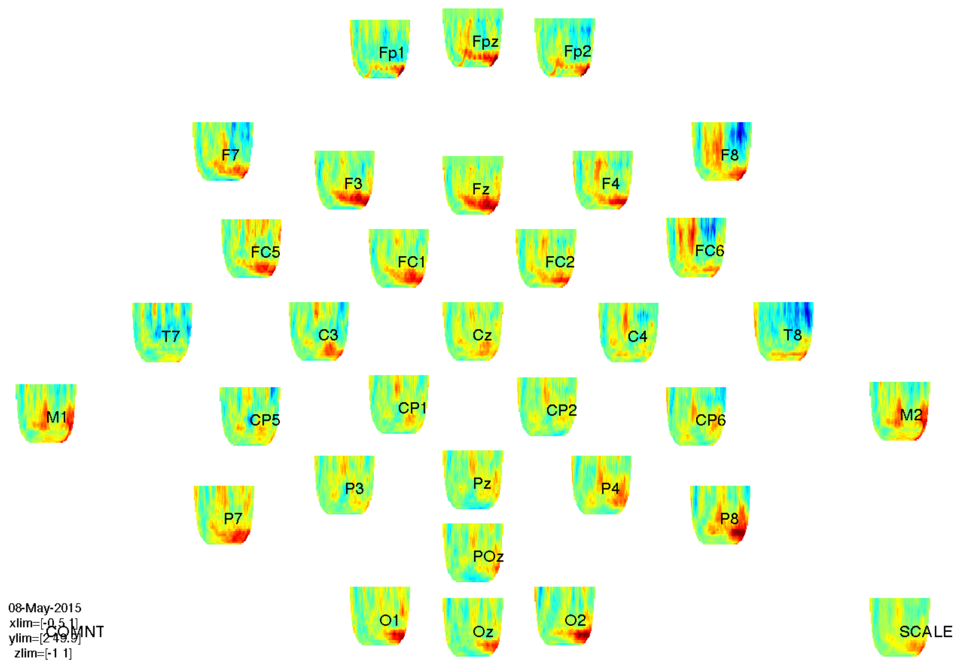


Figure 2.124: First word after *whether* complementizer vs. Control: Alpha band (8-12Hz) masked stats TFR

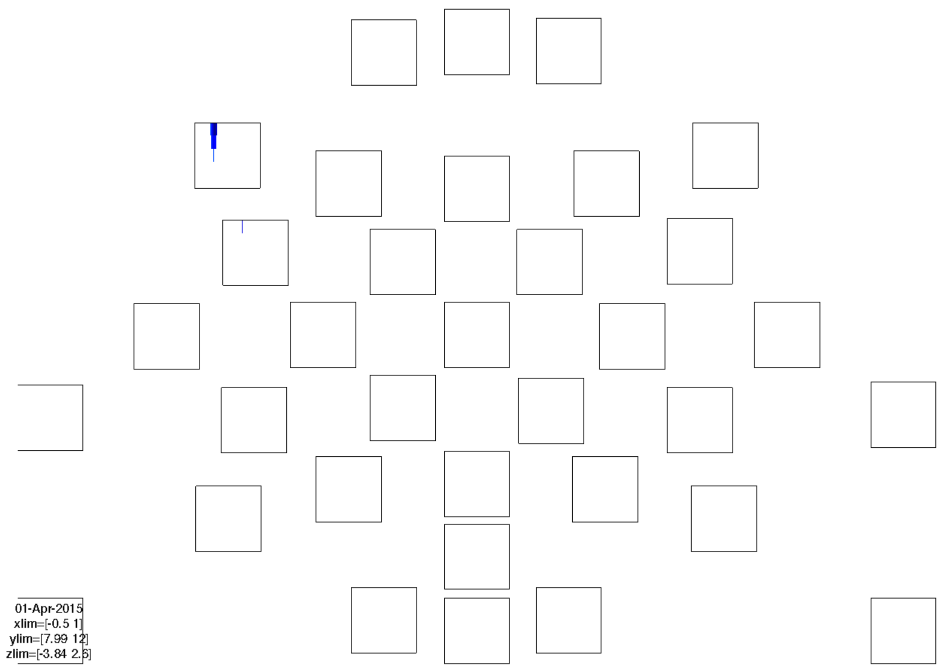


Figure 2.125: First word after *whether* complementizer vs. Control: Alpha band (8-12Hz) masked stats TFR, significant channels

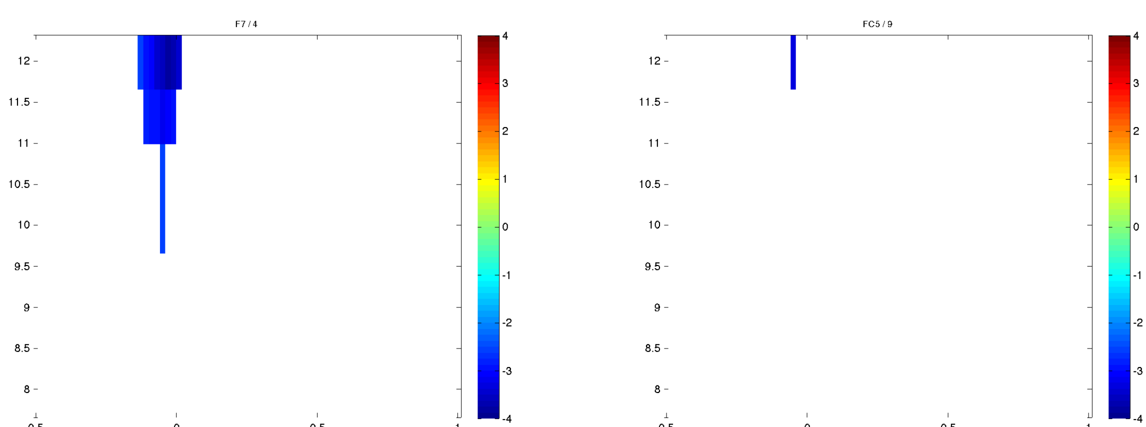


Figure 2.126: First word after *whether* complementizer vs. Control: Lower Beta band (13-20Hz) masked stats TFR

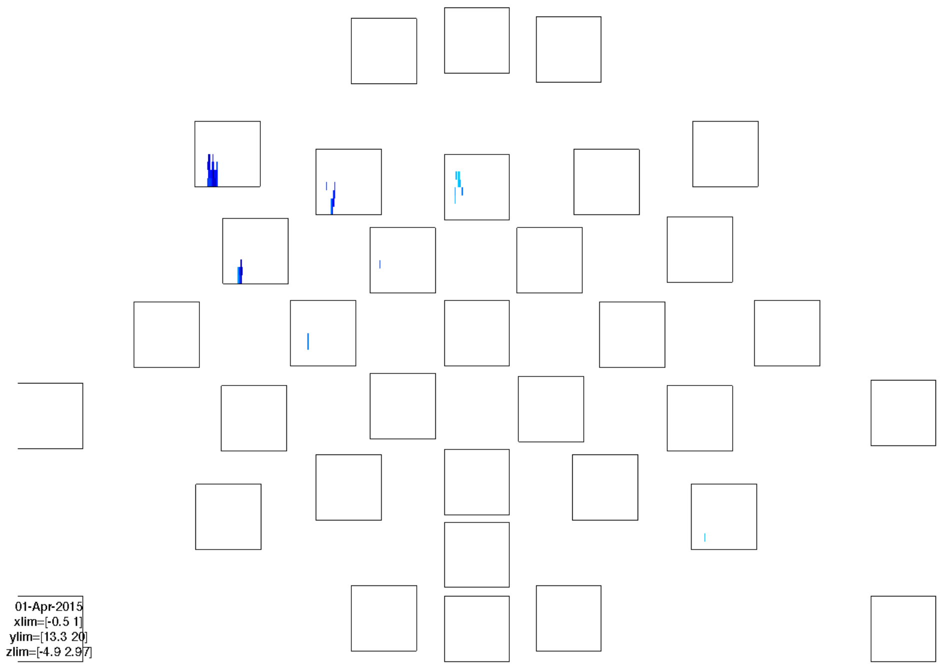


Figure 2.127: First word after *whether* complementizer vs. Control: Lower Beta band (13-20Hz) masked stats TFR, significant channels

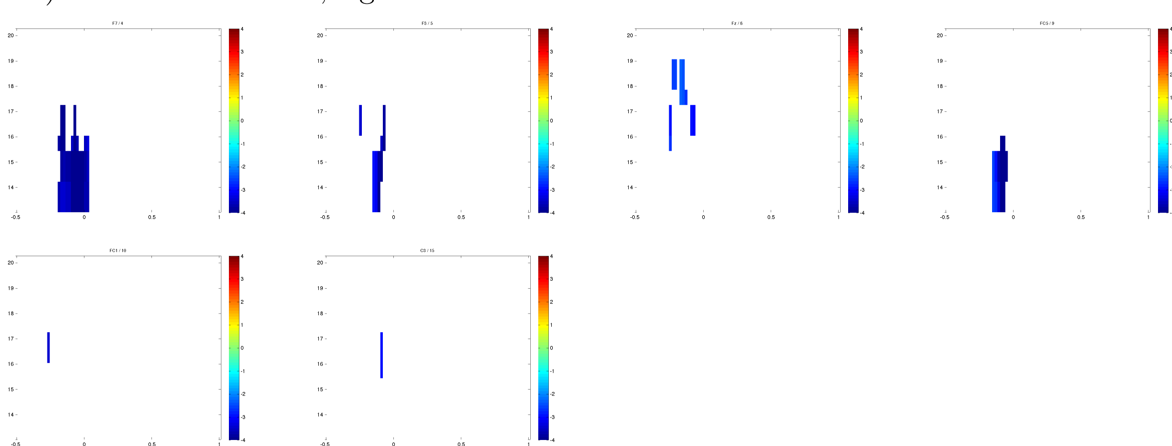


Figure 2.128: First word after *whether* complementizer vs. Control: Upper Beta band (21-30Hz) masked stats TFR

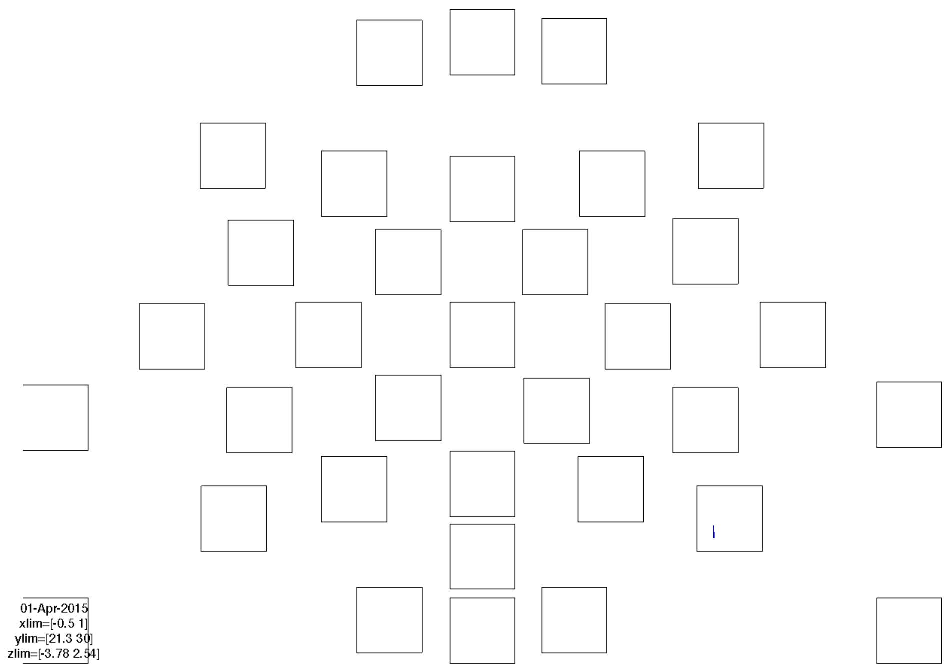
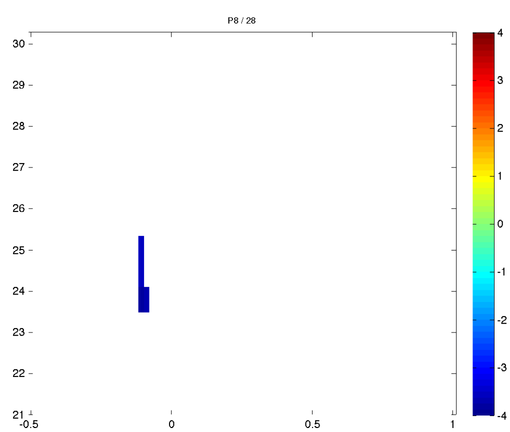


Figure 2.129: First word after *whether* complementizer vs. Control: Upper Beta band (21-30Hz) masked stats TFR, significant channels



2.3 Discussion

2.3.1 Morphosyntactic violations

Table 2.3: LAN Experiment Morphosyntactic Violation Conditions

CC	The cameraman knew that the former mayor would honor *them* before the fireworks.
CV	The cameraman knew that the former mayor would honor *they* before the fireworks.
CONTROL	The cameraman knew that the former mayor would *honor the* soldiers before the fireworks.
θ VIOLATION	The cameraman knew that the former mayor would honor *before* the fireworks.
VAV	The cameraman knew that the former mayor would *honors* the soldiers before the fireworks.

ERPs

In the Case Violation condition there is a broad negative deflection of activity in early time windows, followed by focal but significant positive activity in right posterior areas in late time windows. In the Verb Agreement Violation condition there is only broad significant positive activity in late time windows, concentrated in posterior areas. Lastly, in the θ-Criterion Violation condition there are significant early negativities in *occipital* regions, followed by broad significant positive deflections in later time windows, which are slightly left-lateralized.

Overall, there is evidence of a LAN in the Case Violation condition, and a (posterior) early negativity in the θ-Criterion Violation condition. No such early negativity is apparent in the Verb Agreement Violation Condition, which is in-line with the somewhat elusive nature of the LAN that has been established in previous work.

As for activity in later time windows, there is a (weak) late posterior positivity akin to the P600 in the Case Violation condition, and a robust P600 in both the Verb Agreement and θ -Criterion Violation conditions.

TFRs

In all of the morphosyntactic violations of the LAN Experiment (Case Violations, Verb

Agreement Violations, θ-Criterion Violation), there are decreases in Theta/Alpha/Lower Beta activity (7-16Hz, CV; 7-17Hz, VAV; 6-17Hz, θ-V) activity, which begins ∼450/500ms in posterior areas (occipital, parietal) areas and which move to broad anterior areas, lasting until ∼800ms in the Case and Verb Agreement Violation condition. There are also significant increases in Upper Beta activity (21-30Hz) found in the Verb Agreement and θ -Criterion conditions, in frontal and posterior regions, respectively. Finally, there are central posterior increases in Theta band activity and left anterior increases in Alpha activity in early time windows following Verb Agreement violations.

Finding event-related decreases in Alpha and Beta activity following morphosyntactic violations is consistent with previous work by Davidson & Indefrey (2007), which found similar decreases following phrase structure and agreement violations (associated with P600 positivities).

Decreases in Alpha following ungrammaticalities are relatively unsurprising given the relationship that has been established in the literature between decreases in Alpha activity and (i) increases in cortical activity (Feige et al., 2005; Moosmann et al., 2003; Laufs et al., 2003; Goncalves et al., 2006), and (ii) an increased attentional state (Worden et al., 2000; Thut et al., 2006).

The changes in Beta activity found here are in-line with previous work by Bastiaansen et al. (2010), which found consistent increases in (Lower) Beta (13-20Hz) activity during the processing of grammatical sentences, and interruptions to those increases in (Lower) Beta activity in ungrammatical sentences, at the point of a word category violation. The authors attribute this pattern of activity to syntactic unification operations, which are interrupted by the word category violation. However these results are also consisted with the view that decreases in (Lower) Beta reflect the system's response of unexpected stimuli more generally. Work by Shahin et al. (2009) has also found a combination of increases and decreases in Beta activity (similar to those seen in this work). During a semantic speech processing task, Shahin et al. (2009) found increases in (Upper) Beta activity (25-30Hz), which they attribute to the maintenance of linguistic representations in memory, and decreases in (Lower) Beta activity (13-20) which they characterize as responses to unexpected stimuli. Work by Jenkinson & Brown (2011); Engel & Fries (2010); Kim & Chung (2008) support this latter interpretation, and have found decreases in Beta activity to act as an "index" of the likelihood of new/additional processing demands, based on cues from the past and from the current environment.

It may therefore be the case that the event-related *increases* in Beta activity found here in early time windows represent the maintenance of current representations while previous representations are activated in an attempt to update the now disrupted (thematic) representation of the sentence. Meanwhile, the unlikely nature of the ungrammaticality disrupts what otherwise would be a consistent increase in activity during processing, causing the event-relate (relative) decrease.

Finally, the increases in Theta activity in early time windows following the Verb Agreement Violation may represent what Davidson & Indefrey (2007) describe as an attempt to integrate the meaning of the violation word (here, the main verb) into the sentential context.

In their work, Davidson & Indefrey (2007) found increases in Theta activity in trials with uncertainty, compared with trials in which the violation was clearly detected by a participant (as indexed by an N400 component). In these latter trials, in which the anomalies were clearly detected, the authors suggest that participants did not attempt to integrate the word into the larger context, which correspondingly led to less/no increases in Theta activity in that trial.

Given that Theta activity has been shown to incrementally increase throughout the processing of sentences (Bastiaansen et al., 2010), such stalls in Theta activity as a result of detected violations may lead to event-related Theta decreases like those seen here. Perhaps in the case of the incorrect verbal morphology the violation is harder to detect (in comparison to the use of an incorrect pronoun, or of a word category violation) and participants initially attempt to integrate the verb into the larger sentential context, leading to the early increase in Theta activity in the Verb Agreement Violation condition only, and later the decrease in (primarily posterior) Theta activity seen in all violations.

		Case Violation						Verb Agr. Violation						θ-Criterion Violation					
		left		middle		right		left		middle		right		left		middle		right	
		early	late	early	late	early	late	early	late	early	late	early	late	early	late	early	late	early	late
ERP	anterior														t				
		t													t				
cluster (default)	middle								t						t		t		t
tmax (t)		t					t		t						t		t		t
	posterior	t							t						t		t		
		t					t		t						t	t	t	t	
THETA	anterior																		
	middle																		
	posterior																		
ALPHA	anterior																		
	middle																		
	posterior																		
BETA	anterior		l		l		l	u		u	l		l				u		
					l				l		l		l						
Lower only (l)	middle										l								
Upper only (u)															l				
	posterior								l						l				
															u		l		
GAMMA	anterior																		
	middle																		
	posterior																		

Table 2.4: LAN Experiment: Amplitude (ERP) and Time-Frequency activity following morphosyntactic violations.

2.3.2 Dependencies

wh-items (fillers and non-fillers) vs. control

Table 2.5: LAN Experiment: Wh-words

CONTROL	The cameraman knew *that* the former mayor would honor the soldiers before the fireworks.
WHETHER	The cameraman knew *whether* the former mayor would honor the soldiers before the fireworks.
WHO	The cameraman knew *who* the former mayor would honor before the fireworks.
WHS	The cameraman knew *who* would honor the soldiers before the fireworks.

ERPs

Following the onset of the *wh*-filler *who* in the short-distance dependency condition, there is a broad, marginally significant cluster of negative activity in early time-windows, which is slightly posterior and right-lateralized (perhaps akin to the N400).

Following the (same) *wh*-filler *who* in the long-distance dependency condition, there is a broad, slightly left-lateralized late positivity (with an initial concentration in fronto-temporal channels, similar to the response in the θ-Criterion violation).

In the case of the *wh*-complementizer *whether*, there is both an early negativity (in occipital regions) as well as a late positivity which is significant in left temporal channel 'T7' at ∼450ms, and which is marginally significant in broad areas in late time windows (with an initial concentration in left fronto-temporal areas, similar to both the long-distance dependency filler and the θ-Criterion violation).

The different responses following the the *wh*-fillers is highly unexpected, given that the short- and long- distance dependency conditions are identical up to the point of the *wh*-filler (see Table 2.5). It may be the case that the broad early negativity seen in the short-distance condition (as opposed to the more focal, occipital early negativity seen in the *whether* condition) precludes the late positive-going deflections seen in the long-distance (and *whether*) condition. Why this early negativity does not appear following either of the two other *wh*-items is unclear.

TFRs

For the long-distance condition, there is a right anterior increase in (high) Lower Beta activity (20Hz) in very late time-windows, corresponding to early time windows of the word immediately following the *wh*-filler. In the long-distance condition, this word is the article *the* of the embedded clause subject, which is the first indication to the participant that this is, in fact, a long-distance dependency.

Increases in Beta activity in this range (15-20Hz) have been found in when participants performed delayed tasks, and have been interpreted as the process of maintaining activation of a visual short-term memory representation (see Tallon-Baudry & Bertrand, 1999a; Weiss & Mueller, 2012, for a review). In this case, the representation of the *wh*-filler *who* must be encoded such that it can be accessed at a later point in sentence processing (i.e., once its gap is encountered), a process which may only be fully realized at the point of the word following the *wh*-filler. Previous work by Phillips et al. (2005) has shown that the effects of processing a filler (in their case, an anterior negativity) can last for several seconds after the filler is encountered (an effect which has at times been incorrectly interpreted as a sustained negativity from filler-to-gap (King & Kutas, 1995)). In this case, the increase in Beta activity at the point of the subsequent word may reflect the hold-over of processing of the *wh*-filler in the face of processing an incoming stimulus which is not the dependency's gap.

In the short-distance condition, there are increases in Gamma activity in both early and late time windows, the latter of which also correspond to early time windows of the word immediately following the *wh*-filler, which in the short-distance dependency condition is indicative of the dependency gap (i.e., a modal auxiliary: *would*, *could*, *should* or *might*).

For these early window increases, gamma activity may reflect an increase in attention on the part of the subject (see Jensen et al., 2007, for a review), though it is unclear why this increase in attention would occur for one of the *wh*-dependency conditions and not the other.

For the later-window increases, which overlap with the word immediately following the *wh*-filler, it may be the case that the increased gamma activity reflects processing of the short-distance dependency gap, similar to the increases in activity in central and right posterior areas found in early time-windows of the long-distance dependency gap (see Table 2.3.2). At the point of gap-resolution, memory representations of the filler-item must be integrated with the current sentence representation, processes which have been associated with gamma band activity (Hannemann et al., 2007; Obleser & Kotz, 2011).

These increases in gamma activity in the short-distance dependency condition are correlated with broad early negativities (following both the *wh*-filler and its gap), which may preclude the later positivities observed in both the long-distance dependency and *whether* condition.

Contrary to the increases seen following both of the *wh*-fillers, the *wh*-complementizer *whether* is followed by decreases in (left) anterior Alpha and Lower Beta, and decreases in right occipito-parietal Upper Beta in early-late time windows. These decreases are similar to those found in the morphosyntactic violation conditions (see Table 2.3.1), which supports the theory that decreases in Beta activity are related to the expectedness of a word, rather than to its absolute grammaticality.

		Wh-filler (short)						Wh-filler (long)						Whether					
		left		middle		right		left		middle		right		left		middle		right	
		early	late	early	late	early	late	early	late	early	late	early	late	early	late	early	late	early	late
ERP	anterior								t				t						
cluster (default) tmax (t)	middle								t t				t		t				
	posterior																		
THETA	anterior																		
	middle																		
	posterior																		
ALPHA	anterior																		
	middle																		
	posterior																		
BETA	anterior												l		l		l		
Lower only (l) Upper only (u)	middle														l				
	posterior																		u
GAMMA	anterior																		
	middle																		
	posterior																		

Table 2.6: LAN Experiment: Amplitude (ERP) and Time-Frequency activity following *wh*-words.

First word after a *wh*-item (non-gaps) vs. control

Table 2.7: LAN Experiment: First word after *wh*-item (non-gaps)

CONTROL	The cameraman knew that *the* former mayor would honor the soldiers before the fireworks.
WHETHER	The cameraman knew whether *the* former mayor would honor the soldiers before the fireworks.
WHO	The cameraman knew who *the* former mayor would honor before the fireworks.

ERPs

In response to the word immediately following the *wh*-filler *who* in the long-distance dependency condition compared to control complemented *the*, there is a significant broad early negativity, which is left-lateralized and strongest in anterior channels (akin to the LAN).

In the comparison of the *wh*-complementizer *whether* and the control complementizer *the*, there are no significant changes in amplitude activity.

TFRs

The first word of the long-distance *wh*-dependency has a right anterior increase in Middle Beta (20Hz) activity in early time windows. This increase (as discussed in Section 2.3.2: *wh-items (fillers and non-fillers) vs. control*) in consistent with previous findings of Beta activity increases during the construction and maintenance of working memory representations amidst continuous processing of incoming stimuli (see Weiss & Mueller, 2012, for a review). For example, work by Tallon-Baudry & Bertrand (1999a) found increases in Beta activity (15-20Hz) when participants had to perform delayed tasks.

In response to the first word of the *whether* clause, there are only decreases in frequency activity within the time window of -200ms to word onset (which coincides with the time window of significant decreases in activity found following the *wh*-complementizer *whether*). Therefore no significant changes in frequency power were found following the first word of the whether clause.

		the long-distance dep.						*the* whether					
		left		middle		right		left		middle		right	
		early	late	early	late	early	late	early	late	early	late	early	late
ERP	anterior	t											
cluster (default) tmax (t)	middle												
	posterior												
THETA	anterior												
	middle												
	posterior												
ALPHA	anterior												
	middle												
	posterior												
BETA	anterior					l							
Lower only (l) Upper only (u)	middle												
	posterior												
GAMMA	anterior												
	middle												
	posterior												

Table 2.8: LAN Experiment: Amplitude (ERP) and Time-Frequency activity following the first word after a *wh*-word.

Gaps: short- and long-distance dependencies vs. control

Table 2.9: LAN Experiment: Gaps: short- and long-distance dependencies vs. control

CONTROL	The cameraman knew that *the* former mayor would honor *the* soldiers before the fireworks.
WHO	The cameraman knew who the former mayor would honor *before* the fireworks.
WHS	The cameraman knew who *would* honor the soldiers before the fireworks.

ERPs

Gaps in short-distance dependencies are followed by broad early negativities, which are most concentrated in central posterior areas (perhaps akin to the N400) but which extend from frontal to posterior channels bilaterally.

Gaps in the long-distance dependency condition are followed by more narrow, significant increases in activity in left fronto-temporal channels 'T7' and 'F7' in late time windows, akin to a weak P600. This left fronto-temporal localization is similar to the results from the θ-Criterion Violation condition (see Section 2.3.1), the *wh*-filler *who* and the *wh*-complementizer *whether* (see section 2.3.2: *wh-items (fillers and non-fillers) vs. control*).

TFRs

In the short-distance Dependency condition, the gap of the dependency is realized at the point of the modal auxiliary (e.g., *could*) which immediately follows the *wh*-item *who.*

In the long-distance dependency condition the gap is realized and resolved at the word following the clausal verb, which in this case is the preposition of the adjunct Prepositional Phrase (e.g., . . . *before* *the fireworks.*).

In both the short-distance dependency gap and the long-distance dependency gap, there are only increases in frequency activity. In the short-distance condition, these increases are in right posterior Theta activity in early time windows, and in Upper Beta activity in central posterior areas in late time windows.

In the long-distance dependency, there are also increases in early posterior Theta band activity, though these increases are right-lateralized. There are also left temporal increases in Alpha band activity and broad frontal increases in Beta activity in early time windows. Finally, in the long-distance dependency condition there are additional increases in central and right posterior gamma activity (similar to those seen time-locked to the *wh*-filler *who* in the short-distance dependency, but which coincides with early time windows of the gap of the short-distance dependency.

Increases in Theta band activity following both gaps is perhaps unsurprising, given the established connection of Theta band activity and working memory processes (Klimesh, 1999; Bastiaansen et al., 2010), and in particular retrieval of lexical semantic properties (Bastiaansen et al., 2008). In both of the dependency conditions, the point of the gap represents the point at which the *wh*-filler, and all of its lexical-semantic properties, must be retrieved and integrated with the predicate of the dependency clause.

Given its association with the creation and binding of syntactic units of information (Davidson & Indefrey, 2007; Bastiaansen et al., 2010; Weiss & Mueller, 2012, for a review), and therefore the maintenance (see Tallon-Baudry & Bertrand, 1999a, for a review) and integration (Bastiaansen et al., 2010) of these units, increases in Beta activity following gaps may reflect the activation of memory representations of the *wh*-filler (perhaps Upper Beta), and the maintenance of representations during gap resolution (perhaps Lower Beta).

This would explain why there are increases in Upper Beta activity in not only both of the gap conditions, but in the Verb Agreement and θ-Criterion Violation conditions as well. In all such cases, morphosyntactic cues from the environment may indicate the necessity of a search for a representation for agreement (whether that be syntactic or morphosyntactic). In the long-distance dependency condition, this reactivation leads to gap resolution, which may require additional resources compared with the short-distance dependency given that in the short-distance dependency there are no intervening words between the *wh*-filler and its gap.

The fact that syntactic gaps are not followed by decreases in Beta activity is evidence that they are not unexpected, and therefore that the processes of gap resolution are not triggered by bottom-up information alone. If they were, then the information provided by long-distance gap, for example, would look much like a word category violation (similar to the θ-Criterion Violation condition) and would be followed by *decreases* in Beta activity. On the contrary, those

Finally, increases in Gamma activity at the point of gap-resolution may reflect processes of reactivation and integration (Hannemann et al., 2007; Obleser & Kotz, 2011), which in this case are the reactivation of memory representations associated with the filler-item, and the integration of it with the current sentence representation.

Given that a similar increase in central Gamma activity is found in early time windows for the θ-Criterion Violation, as well as for the dependency gaps, it seems more likely that this increase in activity is related to reactivation processes (given that the semantic representation cannot be updated in the θ-Criterion Violation condition.

		Gap (short)						Gap (long)					
		left		middle		right		left		middle		right	
		early	late	early	late	early	late	early	late	early	late	early	late
ERP	anterior												
									t				
cluster (default)	middle								t				
tmax (t)				t									
	posterior			t									
				t									
THETA	anterior												
	middle												
	posterior												
ALPHA	anterior												
	middle												
	posterior												
BETA	anterior							l		l			
								l					
Lower only (l)	middle							l		u			
Upper only (u)								l				u	
	posterior				u								
GAMMA	anterior												
	middle												
	posterior												

Table 2.10: LAN Experiment: Amplitude (ERP) and Time-Frequency activity following gaps.

Chapter 3

The P600: Grammatical violations and reanalyses

This experiment generates *both* an event-related and time-frequency analysis of a wide-range of P600-inducing and theoretically-related conditions, including (i) garden path sentences, (ii) so-called "thematic P600" sentences, (iii) island violations and (iv) phrase-structure violations (Table 3.1). The results of this experiment contribute intra-experimental ERP contrasts of a variety of P600 'types', and also offer the unique contribution of a spectral characterization of each condition.

The over-arching goal of the experiment is to provide further evidence as to whether the P600 is truly a single electrophysiological response, or if it is a set of responses whose evoked activity shares similar characteristics. Dynamic spectral analysis of P600-inducing conditions will provide characterizations of the frequencies comprising each P600 and the respective time-course information of those frequencies. If the the time frequency (TF) representations of the P600s generated in response to the conditions are found to involve similar frequencies as well as their similarities in topography and latency, then this will be evidence for the necessity of a joint account of the responses. This will be evidence against a purely syntactic account of the response, given the qualitative distinctions in the eliciting syntactic conditions. However, if each of the TF representations has distinct signature frequencies, this may be evidence for qualitatively different processes from topographically similar networks at play in each of the responses.

3.1 Methods

3.1.1 Participants

25 men and women, all students from University of California, Irvine participated in this experiment (5 male; mean age 19 years and 20 female; mean age 19.55 years). All participants were healthy native speakers of English. All subjects had normal or corrected-to-normal vision, and were right-handed. Subjects on average scored within the 10^{th} decile of right handedness (97.74 laterality index) according to an online adaption of the Edinburgh handedness survey (Oldfield, 1971), with a median laterality of 100. All participants gave informed consent and were paid $10/hour for their participation, which lasted approximately 2 hours, including set-up time.

3.1.2 Stimulus Materials and Experimental Design

Our experimental materials consisted of 32 octuplets of English sentences, representing one sentence of each of our eight experimental conditions: (1) Garden Path Control, (2) Garden Path, (3) Thematic P600 Control, (4) Thematic P600, (5) Island Violation Control, (6) Island Violations, (7) Phrase Structure Violation Control, and (8) Phrase Structure Violations. (Table 3.1). Conditions (1), (3), (5), (7) serve as fillers for conditions (2), (4), (6), and

(8). All materials were adapted from materials of previously published experiments (one per each condition). Two lists of 32 sentences were created for each of the four conditions (garden path, island violations, phrase structure violations, Thematic P600s) using materials of Osterhout & Holcomb (1992), McKinnon & Osterhout (1996), Neville et al. (1991), and Kim & Osterhout (2005), respectively.

Table 3.1: P600 Experimental conditions

GPC	The woman heard that the broker intended *to* conceal the transaction at the meeting.
GPV	The woman heard that the broker persuaded *to* conceal the transaction was sent to jail.
THC	The woman suspected that the murder was *witnessed* by three bystanders.
THV	The woman suspected that the murder was *witnessing* the three bystanders.
ISC	I wonder whether the candidate was annoyed *when* his son was questioned by one of his staff.
ISV	I wonder who the candidate was annoyed *when* his son was questioned by.
PSC	Jill heard that the students discussed Frank's *speech* about migrants.
PSV	Jill heard that the students discussed Frank's *about* speech migrants.

Once the sentence sets were created, eight stimulus lists were generated using a Latin square design, resulting in 32 unique tokens of each condition on each list. This ensured that no two sentences in any given list were from the same original sentence set. Following this, each of the eight stimulus lists were turned into eight unique, pseudorandomly-ordered lists, using a random number generator and manual adjustments in cases where a single condition appeared multiple times in a row.

Participants were shown the ordered lists according to their participant number, with Participants 1-8 seeing Lists 1-8, respectively, Participants 9-16 seeing Lists 1-8, respectively, and so on. In the end, Lists 2-8 were shown to three participants (e.g, List 1 was shown to P1, P9, P17, P25), and List 8 was shown to three participants (P8, P16, P24).

Each stimulus sentence of the ordered lists was followed by a *probe word* (presented in red), half of which were *open-class*, and half of which were *closed-class*. Half of the probe words used were present in the preceding sentence (*true*), and half of them were not (*false*). Furthermore, the position the probe word either *did* come from (in the case of a *true* probe word) or *could have* come from (in the *false* probe word case) was equally distributed among the possible *open-* and *closed-class* positions for every condition (between 10 and 15 positions depending on the condition)[1]. The features *open-* or *closed-*, *true* or *false*, and *position #* were pseudorandomly assigned such that equal numbers of each were used. For cases where the probe word was *false*, a word from the corresponding position was chosen from another sentence.

3.1.3 Procedure

Before the experiment, each participant was given both verbal and written information about the EEG equipment and measurement procedures, as well as the design of the experiment and their instructions for participation. Any questions participants' had about the experiment were answered immediately. Following this, participants' completed an informed consent form, as well as an online English version of the Edinburgh Handedness Inventory.

The experiment took place in a dimly lit testing room, where participants were comfortably seated at a desk in front of a computer monitor. All experimental stimuli (other than the probe words) appeared in yellow on a blue background, in 48 pt font. Probe words were presented in red on the same blue background in the same font size. Every sentence was preceded by a fixation, which appeared in the center of the screen for 1000ms. Following the fixation, a blank screen appeared for 300ms. Sentences were presented one word at a time, with each word appearing for 300ms, followed by a blank screen for 300 ms. The one exception to this was the last word of each sentence, which appeared for 1000ms and was marked with a period. The last word was followed by a blank screen for 300ms, which was then followed by a probe word, presented for five seconds.

[1]For *true* probe words, there were between five and seven open- class positions (maximum: subject noun, matrix verb, adjective modifying the embedded subject, embedded subject noun, embedded verb, embedded direct object (when pronouns were not used), and embedded indirect object noun), and 4-5 closed-class positions (multiple instances of 'the' were not counted). An example of the positions in a stimulus sentence is shown in Table 2.2.

Participants were instructed to read sentences without blinking or moving, and to indicate with a button press whether the probe word that appeared on the screen had appeared in the preceding sentence. No feedback was provided. Prior to any stimulus materials, each participant was shown an identical list of 20 sentences that constituted a practice session, lasting approximately 4-5 minutes. The experimental session that followed was divided into 16 blocks of 16 sentences, each of which lasted approximately 4-5 minutes. Between each block, a screen appeared indicating that the participant should take a break. Participants were able to control the length of their breaks, which were ended when they pressed a button that recommenced the experiment. Each participant's session, including informed consent, equipment preparation, practice, experimental blocks and debriefing, took approximately 120 minutes.

3.1.4 EEG Recording

EEG was recorded from 32 Ag/AgCl electrodes mounted in an electrode cap (Electrocap International): (midline) FPz, Fz, Cz, Pz, POz, Oz, (lateral) FP1/2, F3/4, F7/8, FC1/2, FC5/6, C3/4, CP1/2, CP5/6 T7/8, P3/4, P7/8, O1/2, and (mastoids) M1/M2. EEG was recorded with an average reference, with no online filtering. Data was re-referenced to linked mastoids for consistency with the literature.To monitor eye movements, an additional bipolar electrode was placed on the right and left outer canthus, and another bipolar electrode was placed above and below the left eye. EEG and EOG recordings were amplified and sampled at 1024Hz. Impedances were kept below 5 kΩ.

3.1.5 Preprocessing

Data analysis was performed using the EEGLAB (Delorme & Makeig, 2004, `http://sccn.ucsd.edu/eeglab/`)), ERPLAB (Lopez-Calderon & Luck, 2014, `http://erpinfo.org/erplab`)), and Fieldtrip (Oostenveld et al., 2011, `http://www.fieldtriptoolbox.org/`)) software packages, all of which are Matlab toolboxes used for the analysis of EEG and MEG data.

For both the amplitude and time-frequency analyses, trials containing ocular, muscle or other large artifacts were identified and removed based on visual inspection (22.8% total). Data from 3 subject(s) was excluded as a result of excessive artifacts, leaving a total of 22 participants.The number of excluded trials was not significantly different between conditions ($F_{7,192} = 0.25, p = 0.97$), resulting in an average of 23.2 trials per condition for each subject.

3.1.6 Event-related Potential Analysis

Note: Methods described here are identical to the methods described in Chapters 2 (Section 2.1.6)and 4 (Section 4.1.5), but are reproduced here for the convenience of the reader.

For the ERP analysis, stimulus sentences were first segmented from the larger EEG using boundary markers, and channels were re-referenced to the average of the two mastoid channels. The resulting sentence segments were high-pass filtered at 0.1Hz using a second-order butter worth filter, and DC bias was removed. Event epochs were then segmented 200ms before to 1000ms after each critical word, and the resulting epochs were low-pass filtered at 30Hz with a second-order butterworth filter. Trials containing artifacts were removed, and the remaining trials were grand averaged at each channel.

Statistical comparisons of the resulting condition grand average ERPs were made using the Mass Univariate ERP Toolbox (Groppe et al., 2011, `http://openwetware.org/wiki/Mass_Univariate_ERP_Toolbox`). The *mass univariate analysis* (Woolrich et al., 2009) approach is an answer to the coarse nature of more typical ERP analyses, which compare average activity across swaths of electrodes and time points. The t_{max} and *cluster-based* approaches in particular were chosen, based on recent work showing their robustness in cases where data is highly correlated (Hemmelmann et al., 2004).

t_{max} permutation tests

The ERP difference waves for each pair of the conditions were analyzed with a repeated-measures two-tailed permutation test based on the t_{max} statistic (Blair & Karniski, 1993), with a family-wise error rate of α=0.05. Activity from each of the 30 non-reference channels (mastoids excluded) were compared in two time windows of interest, which were selected as windows in which the LAN (200-500ms, 9216 comparisons) and P600 (400-900ms, 15360 comparisons) were commonly identified in previous research. In this permutation, a t-test was performed for each channel$\times$time point, using the original data and data from 2500 random, within-subject permutations of each subject's data (2500 permutations is suggested by the literature as it is more than twice the number recommend by Manly (2006) to achieve a family-wise α of 0.05). From each of the tests, the most extreme t-score was selected and a distribution of these "t_{max}" scores was estimated. The t_{max} score from the original data was then compared against this estimated distribution, as a non-parametric approach to the statistical comparison (Maris, 2004). Based on these estimates, a critical t-score was established, and any data exceeding that value was marked as significant.

cluster-based permutation tests

In addition to permutation tests based on the t_{max} statistic, a series of repeated measures, two-tailed *cluster-based* permutation tests were also performed for the time windows of interest (200-500ms and 400-900ms), using the cluster mass statistic (Bullmore et al., 1999) and a family-wise α level of 0.05. Cluster permutation tests were computed in a manner fairly similar to the t_{max} approach, with repeated-measures $t-$tests performed on the original data and 2500 random permutations of the data, however in this case t-scores less than a threshold α (here 0.05) were selected at each permutation and summed in *clusters*. The most extreme resulting cluster sum or "mass" at each permutation was then used to estimate the null distribution. With this, the permutation cluster mass percentile ranking of each cluster in the actual data was used to calculate a corresponding $p-$value, and that $p-$value was then assigned to all channels in the cluster.

Following this, a second round of cluster-based tests were performed using a more relaxed α threshold of 0.08, and a similarly relaxed FWER (α=0.08).

Clusters were determined based on spatial and temporal features, with electrodes within 5.77 cm of each other considered spatial neighbors and adjacent time points considered temporal neighbors. Given these parameters, the median number of channels per cluster was 4, with a minimum of 2 channels and a maximum of 6 in a cluster.

An advantage of the cluster-based approach is that it captures the broader regional effects (activity extending across several electrodes) often seen in ERPs (e.g., the P300), and is thought to be the most powerful mass univariate procedure to detecting broadly distributed effects (Groppe et al., 2011; Maris & Oostenveld, 2007)

3.1.7 Time-Frequency Analysis

Note: Methods described here are identical to the methods described in Chapters 2 (Section 2.1.7)and 4 (Section 4.1.6), but are reproduced here for the convenience of the reader.

Time-frequency representations of the activity surrounding the critical word of each condition were created using the software package Fieldtrip (Oostenveld et al., 2011), on event epochs -500ms to 1000ms after the onset of the critical word. In a fashion somewhat similar to the preprocessing steps of the ERP analysis, epochs were extracted from the data, were baselined according to the average activity prior to the critical word onset, were detrended to remove any large, non-meaningful drifts in the data, and were rereferenced to the average of the two mastoid channels. Frequency activity within the window was then estimated in steps of 20ms, using a multitapered Fourier analysis approach with 'sliding' (and overlapping) Hanning windows.

In this type of analysis, a window containing a pure sine wave of a given frequency is convolved with the data for an estimate of the average activity at that frequency within the duration of the window. Windows of 5 cycles (5 wavelengths) were used to estimate activity in each frequency between 2 and 50 Hz, in 1 Hz steps. The length of the window was determined by the frequency being measured, which optimized the time×frequency trade-off in precision. With this approach, smaller windows could be used to estimate higher frequencies, increasing the temporal precision of the estimate. Furthermore, frequency window edges were smoothed in order to avoid edge effects in the estimates, by multiplying the frequency wave with an inverted cosine (the properties of which were a function of frequency as well). The result of this is a Hanning (Hann) window. Because tapering in the Hanning window necessarily means the loss of data at either edge of the window in each estimate, the estimates made using the window were overlapping (the window was successively 'slid' to the right, to an extent determined by the number of time points estimated for each frequency - here in steps of 20ms). This type of analysis has been used in similar existing work examining the brain's response to sentence processing (Bastiaansen & Hagoort, 2006, e.g.).

In this TF analysis, the baseline window was extended from the -200ms used in a typical ERP analysis to -500ms, to accommodate a minimum 2Hz frequency resolution of the baseline window. Furthermore, given that the smallest frequency activity examined statistically was 4Hz, this baseline window allowed for at least two wavelengths of each frequency in the baseline window (a standard preferred for our analysis).

Finally, the resulting TFRs were averaged for each subject to create a representation of changes in induced frequency activity for each subject (Tallon-Baudry & Bertrand, 1999b). Subsequently, a statistical comparison of each condition was computed using the monte-carlo estimate of non-parametric significance probabilities (using permutation methods similar to those in the ERP analysis). In this case, in each statistical comparison the labels for each condition for each subject were randomly shuffled between conditions/subjects a large number of times, and each time a two-tailed dependent sample t-statistic and corresponding p-value were calculated, estimating the probability distribution for the null hypothesis.

The number of permutations used was determined as a function of the critical α value (here, 0.01), which was divided by the inverse of the number of comparisons (the number of channels$\times$frequencies$\times$time points) for each of five frequency bands. This number was multiplied by 1000, resulting in a number of permutations between 10,000 and 20,000.

3.2 Results

3.2.1 ERPs and TFRs

Garden Path

GPC The woman heard that the broker intended *to* conceal the transaction at the meeting.
GPV The woman heard that the broker persuaded *to* conceal the transaction was sent to jail.

ERPs

In a comparison of the Garden Path Condition with the Control Control condition, there is a visible negative going deflection at 100 and 200mspost cw-onset, and a visible positive going deflection in left fronto-temporal and later right occipital areas from 500 to 900ms post cw-onset. T_{max} permutation tests reveal significant negative activity in occipital channels bilaterally at ∼475ms (Fig. 3.3).Cluster-based permutation tests with cluster α and FWER α = 0.08 reveal broad, marginally significant clusters of early negative activity, between ∼200-400ms (Fig. 3.5).

Figure 3.1: Garden Path Violation: ERPs

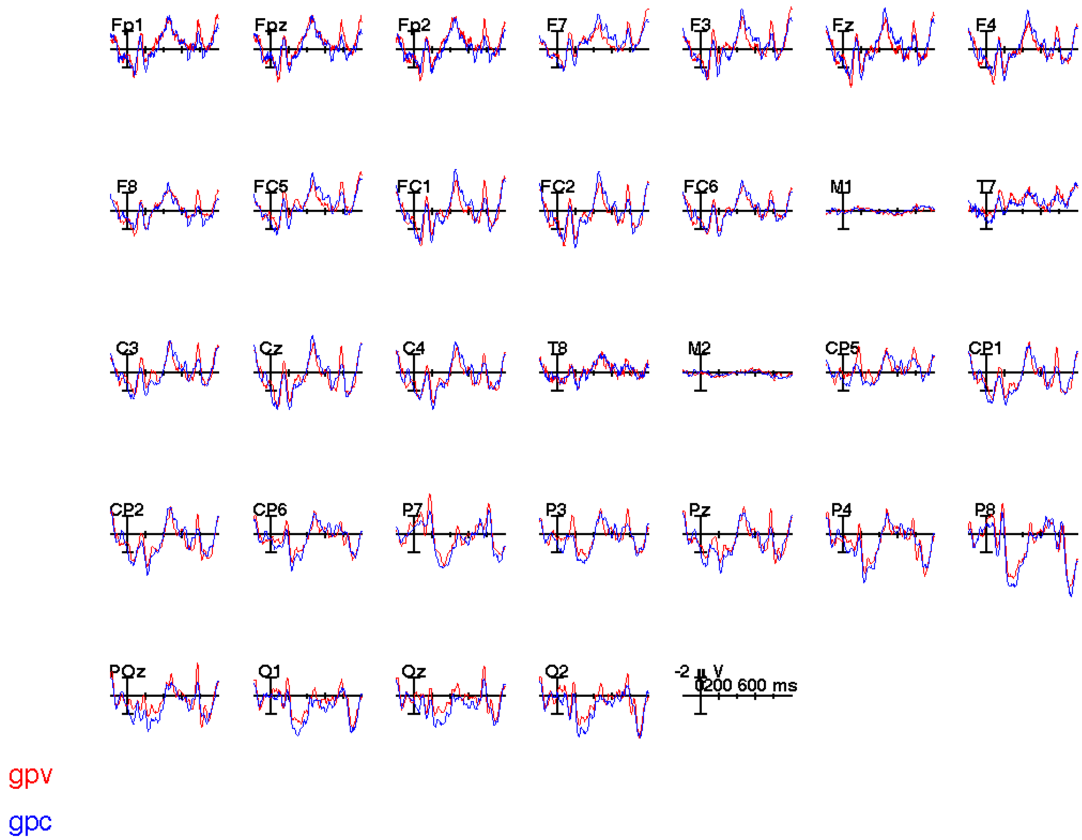
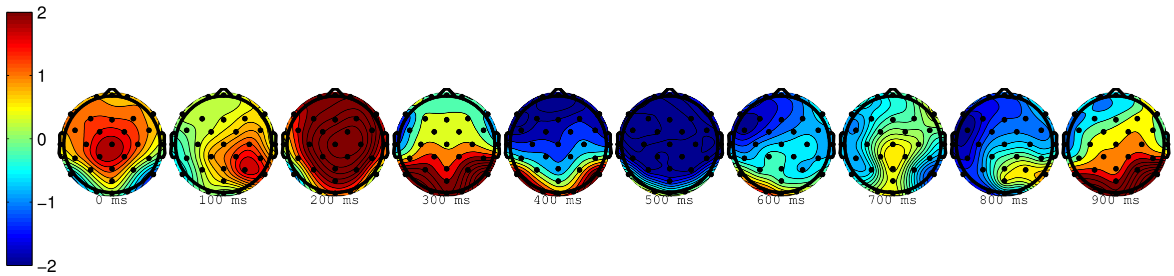
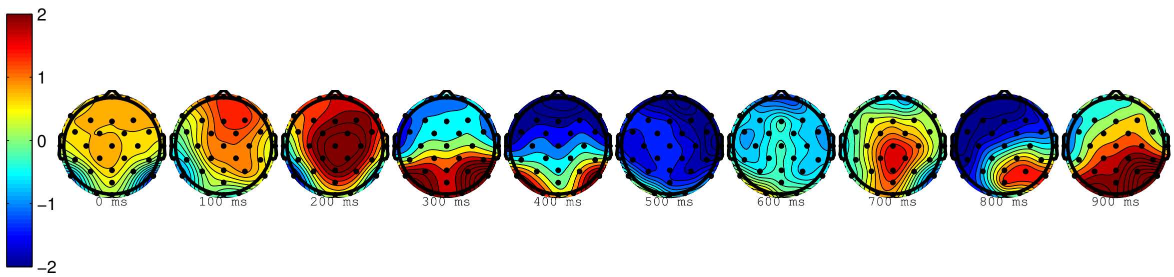


Figure 3.2: Garden Path Violation: topoplots

Garden Path Control



Garden Path Violation



Difference plots

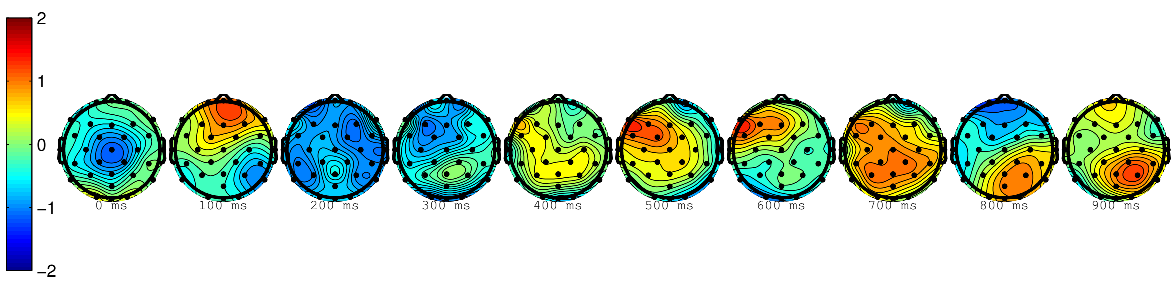


Figure 3.3: Garden Path Violation: t_{max} permutation tests

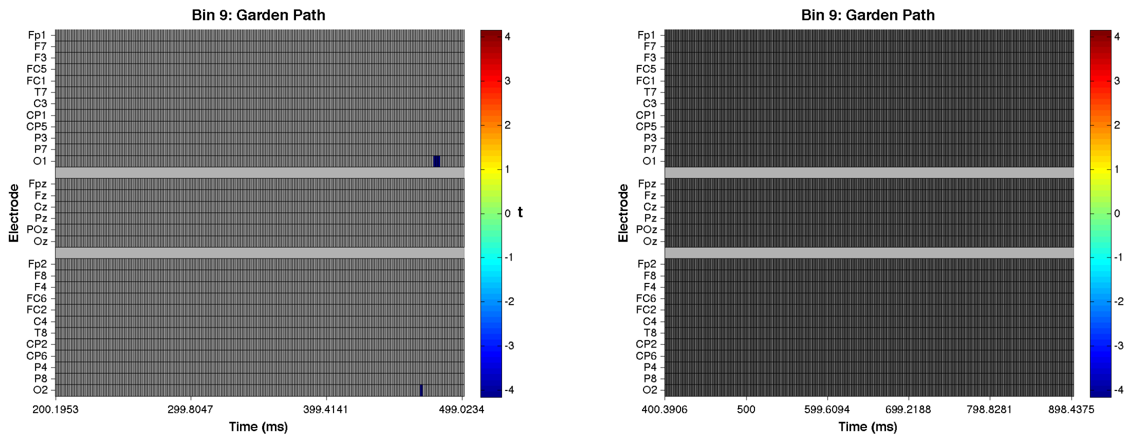


Figure 3.4: Garden Path Violation: cluster mass permutation tests

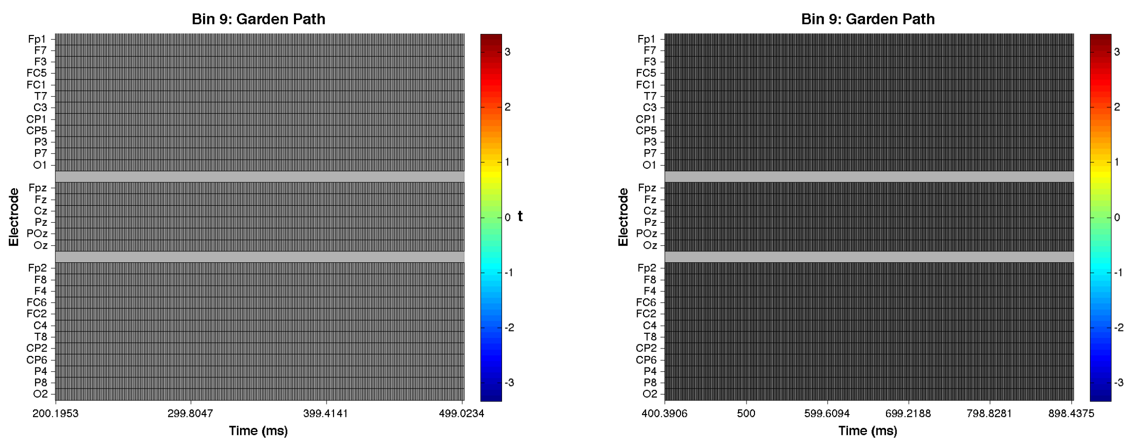
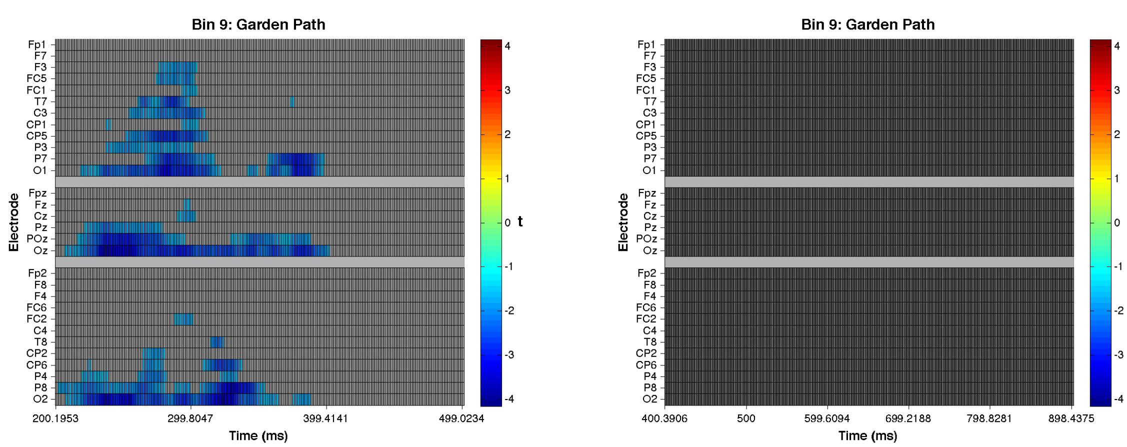


Figure 3.5: Garden Path Violation: cluster mass permutation tests (cluster alpha =0.8)



TFRs

Comparing the Garden Path and Garden Path Control conditions, there is a significant occipital decrease in 9-12Hz activity at ∼450ms in the Garden Path condition, as well as significant decreases in left anterior areas in the range of 13-26Hz at ∼500ms, and decreases in right occipito-parietal areas in the range of 13-20Hz activity at ∼500ms as well. These decreases are followed by an increase in in 18-22Hz activity in right occipito-parietal channels between ∼850-900ms.

Overall, in the Garden Path Violation condition, Alpha band activity decreases in occipital areas at ∼450ms, followed by decreases in Lower and Upper Beta activity in left anterior areas at ∼500ms, and decreases in Lower Beta activity in right occipito-parietal areas at ∼500ms as well. Finally, these decreases are followed by an increase in Lower and Upper Beta activity in right occipito-parietal areas between ∼850-900ms.

Figure 3.6: Garden Path Sentences: TFR

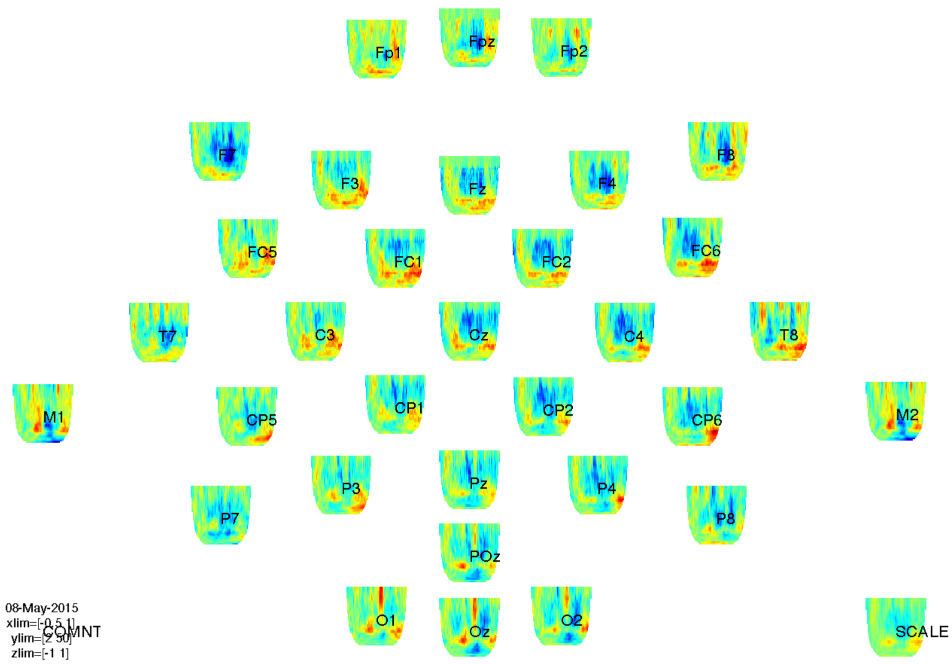


Figure 3.7: Garden Path Violation: Alpha band (8-12Hz) masked stats TFR

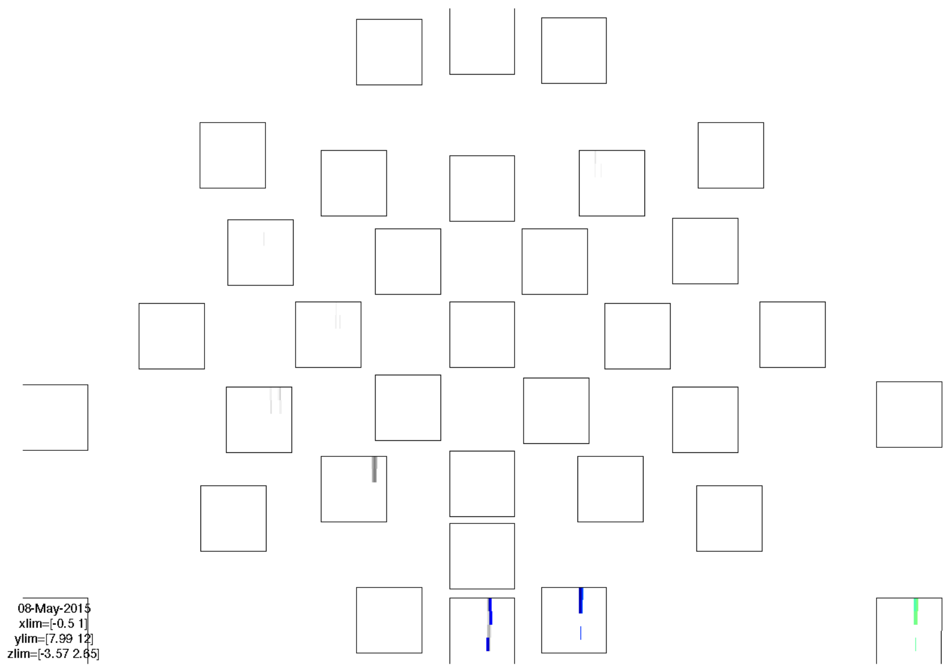


Figure 3.8: Garden Path Violation: Alpha band (8-12Hz) masked stats TFR, significant channels

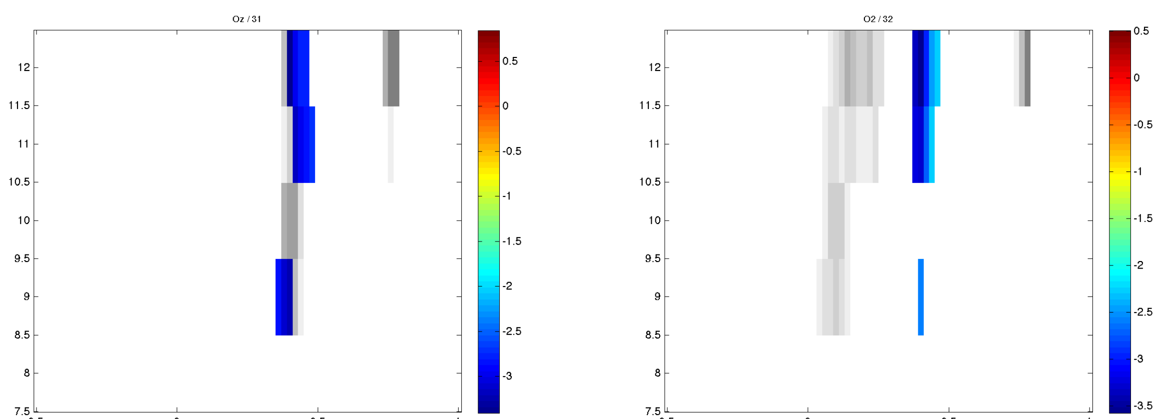


Figure 3.9: Garden Path Violation: Lower Beta band (13-20Hz) masked stats TFR

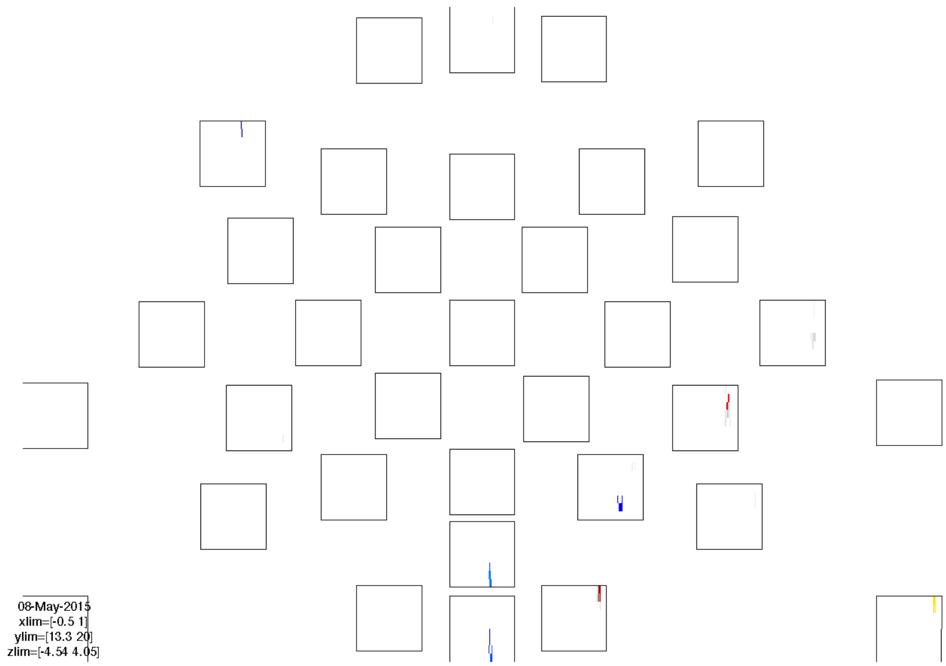


Figure 3.10: Garden Path Violation: Lower Beta band (13-20Hz) masked stats TFR, significant channels

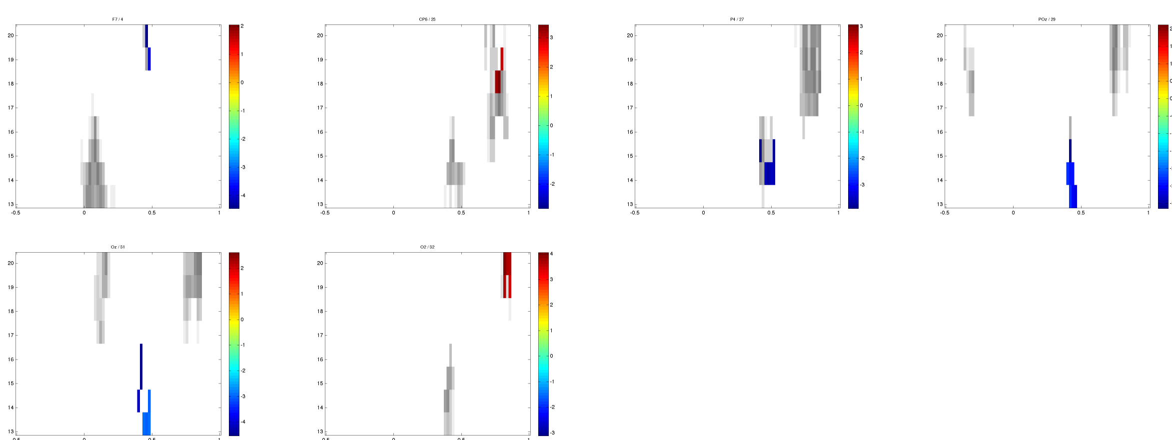


Figure 3.11: Garden Path Violation: Upper Beta band (21-30Hz) masked stats TFR

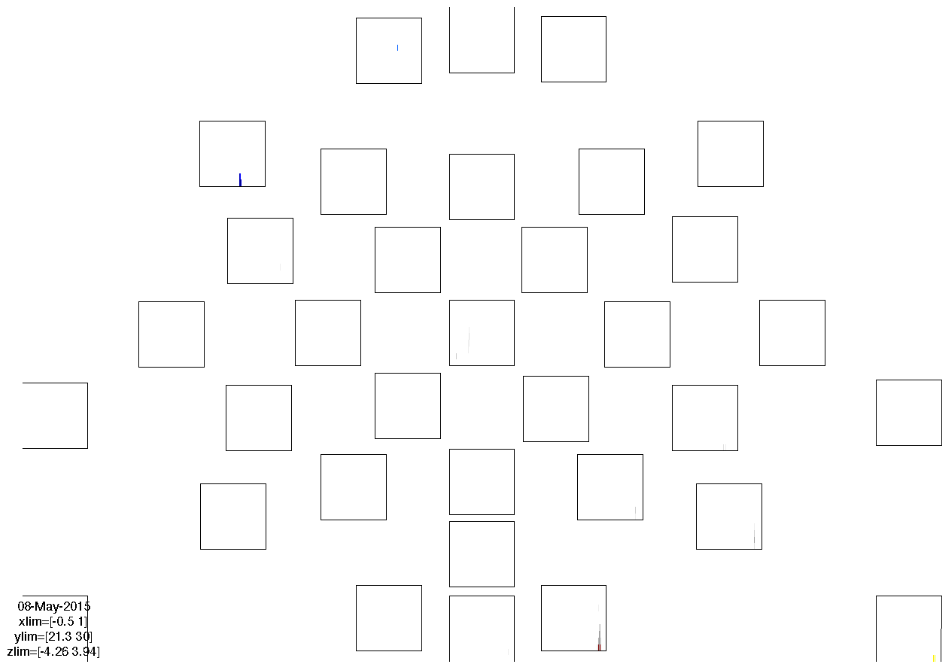
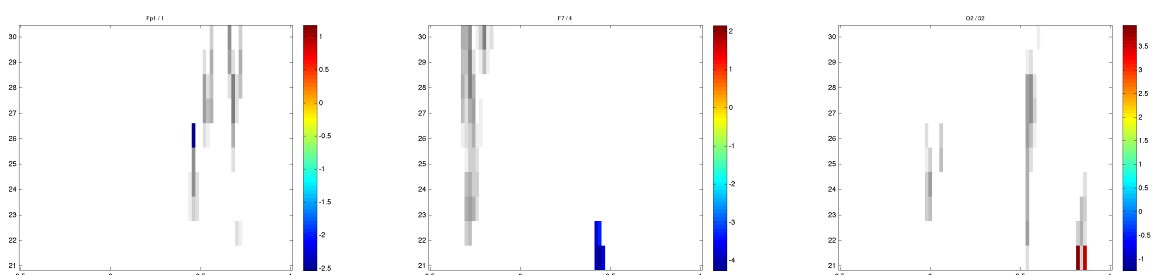


Figure 3.12: Garden Path Violation: Upper Beta band (21-30Hz) masked stats TFR, significant channels



Thematic P600s

THC The woman suspected that the murder was *witnessed* by three bystanders.
THV The woman suspected that the murder was *witnessing* the three bystanders.

ERPs

In a comparison of the Thematic P600 condition with the Thematic P600 Control condition, there is a visible negative going deflection in topoplots of instantaneous amplitude, beginning at 200ms and continuing throughout 900ms. These negative deflections are visible in varying topographies, beginning with widespread deflections at 200ms, moving to occipital areas at 300 and 400ms, to widespread negative deflections again at 500 and 600ms, and finally to right frontal areas from 700-900ms. T_{max} permutation tests reveal significant negative activity in right anterior channels at ∼200ms, followed by significant negative activity in (left-biased) occipital channels between ∼400-500ms (Fig. 3.15). Cluster-based permutation tests reveal significant clusters of negative activity broadly, with a right hemisphere bias, between ∼400-500ms (Fig. 3.16). When the cluster permutation test parameters are relaxed to α and FWER $\alpha = 0.08$, marginally significant clusters of early negative activity, in primarily occipital channels are found, between ∼300-400ms (Fig. 3.17).

Figure 3.13: Thematic P600: ERPs

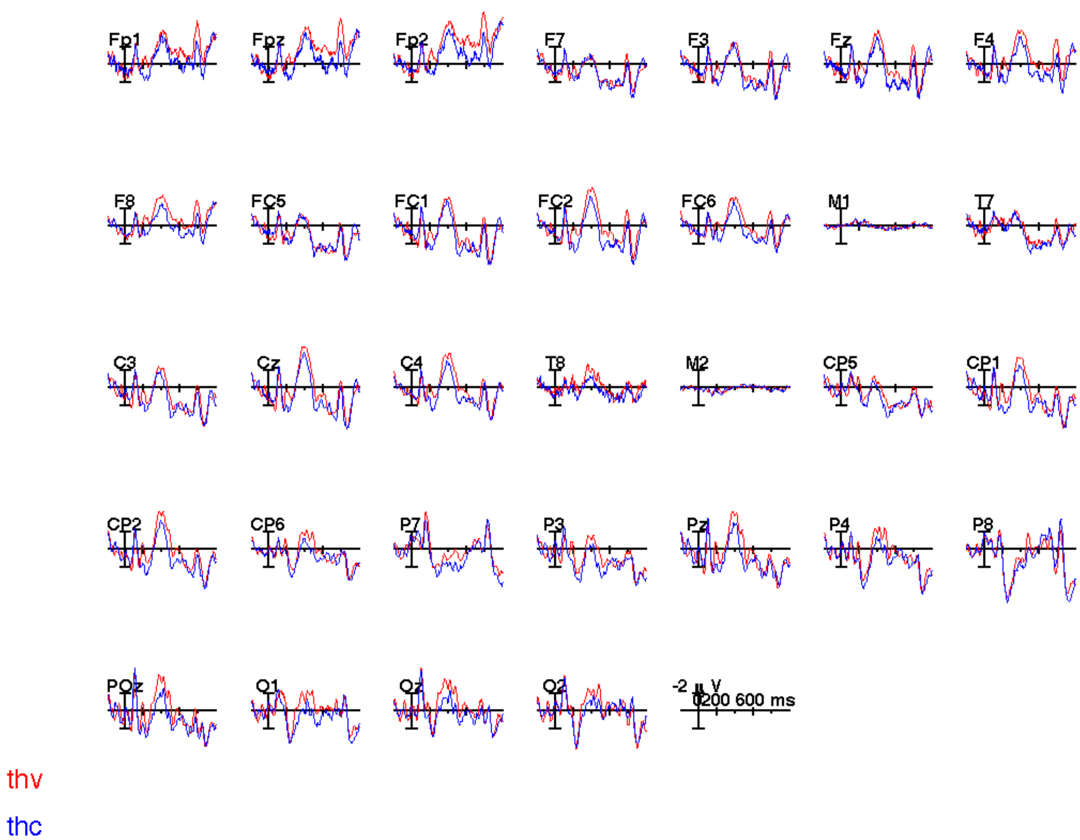
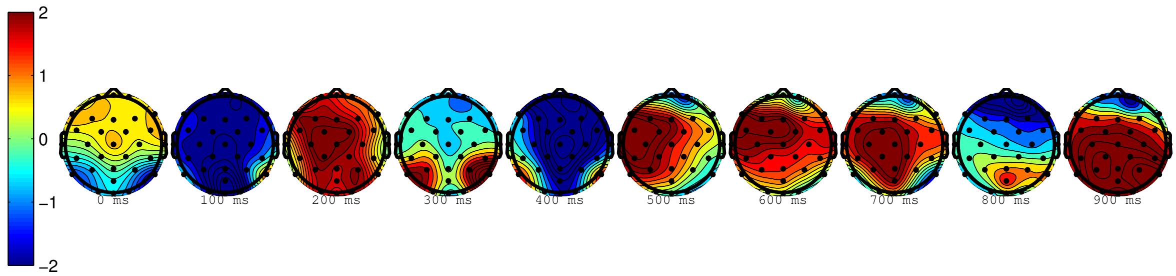
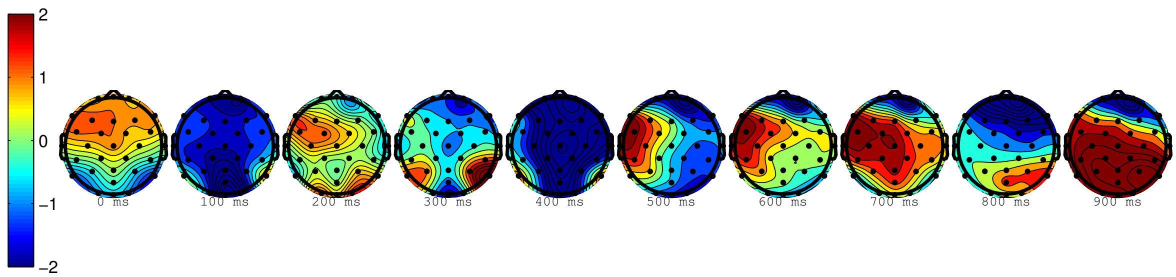


Figure 3.14: Thematic P600: topoplots

Thematic P600 Control



Thematic P600



Difference plots

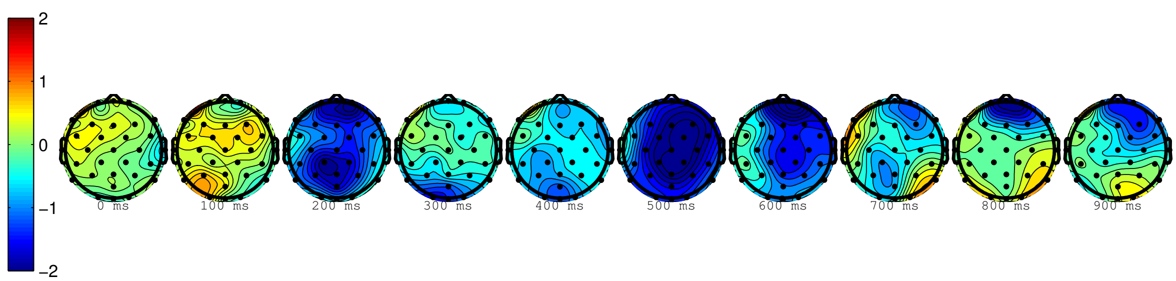


Figure 3.15: Thematic P600: t_{max} permutation tests

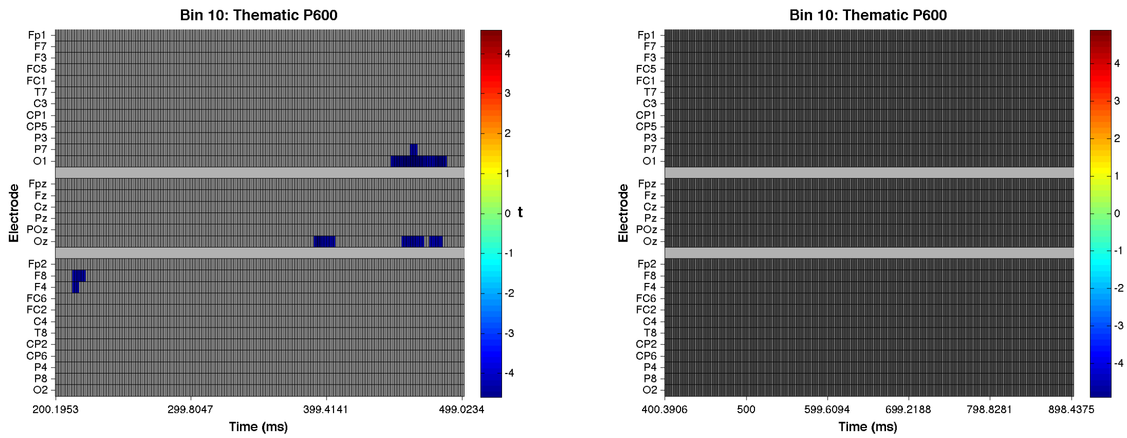


Figure 3.16: Thematic P600: cluster mass permutation tests

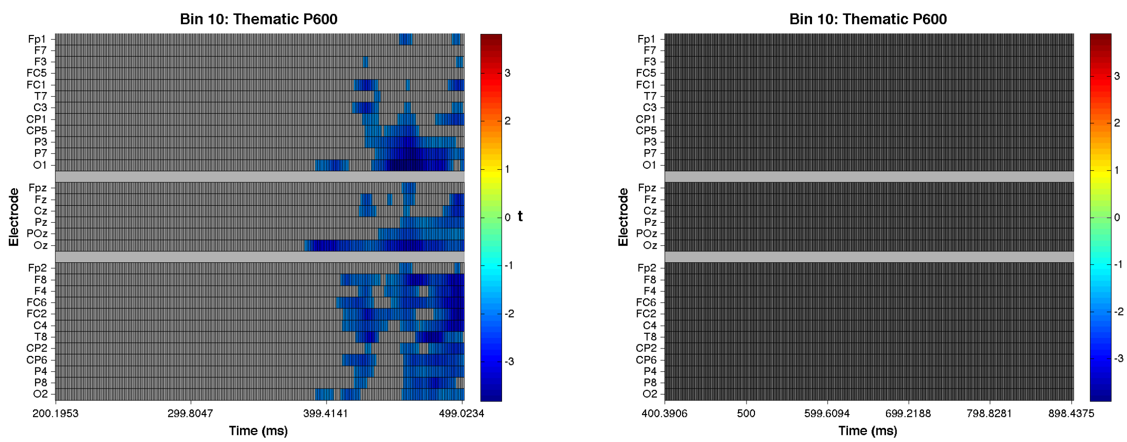
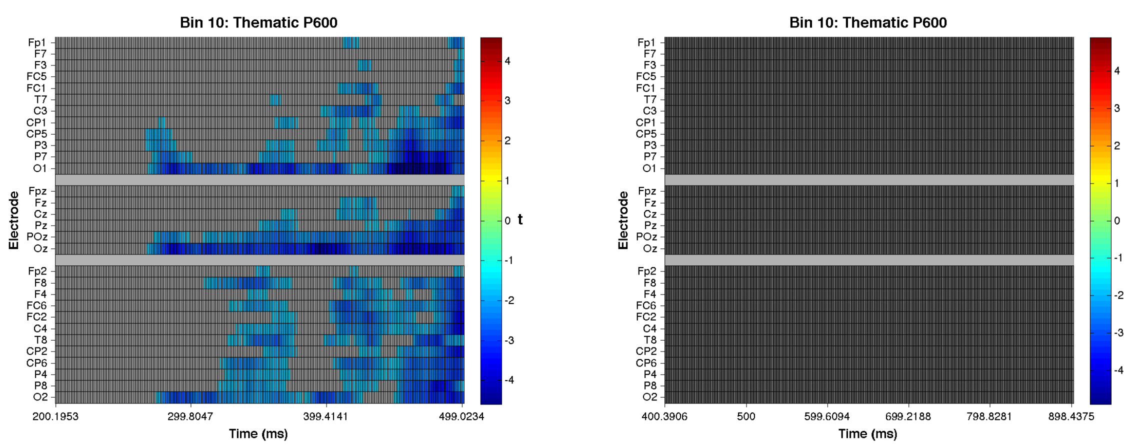


Figure 3.17: Thematic P600: cluster mass permutation tests (cluster alpha=0.8)



TFRs

Comparing the Thematic P600 and its corresponding Control condition, there is a left occipito-parietal decrease in 21-28Hz between ∼400-550ms, a decrease in 9Hz activity in left parietal areas at ∼500ms, a decrease in left anterior activity at 11Hz at ∼600ms, a widespread decrease in 17-20Hz activity between ∼500-600ms, and a significant decrease in right central areas in 7Hz at ∼650ms.

Overall, in the Thematic P600 condition, Theta band activity decreases in right central areas at ∼650ms, Alpha band activity decreases in left parietal areas at ∼500ms and in left anterior areas at ∼600ms, Lower Beta activity has a widespread decrease between ∼500-600ms, and Upper Beta activity decreases in left occipito-parietal areas between ∼400-550ms.

Figure 3.18: Thematic P600 Sentences: TFR

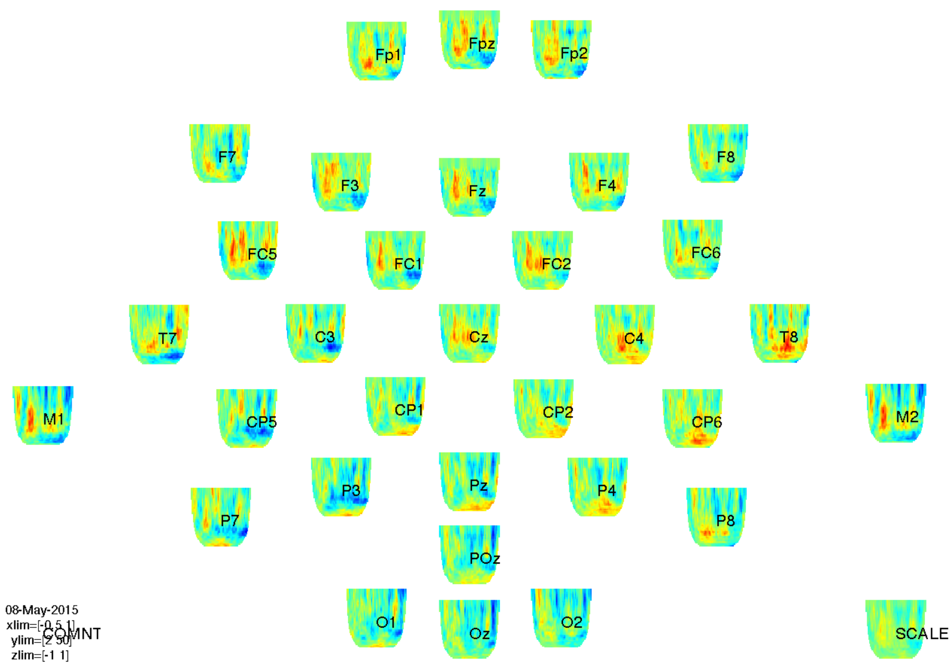


Figure 3.19: Thematic P600: Theta band (4-7Hz) masked stats TFR

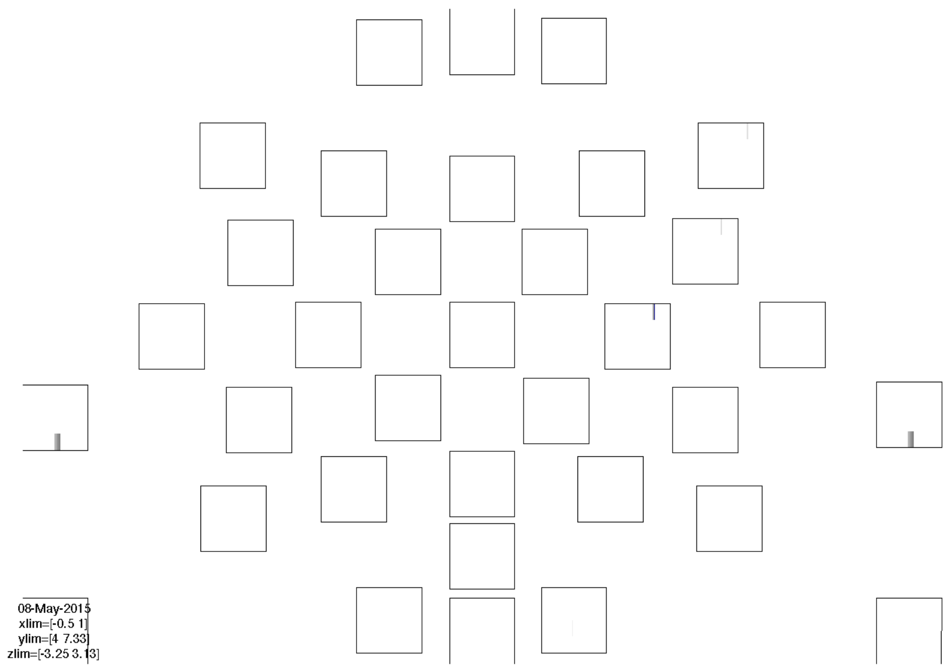


Figure 3.20: Thematic P600: Theta band (4-7Hz) masked stats TFR, significant channels

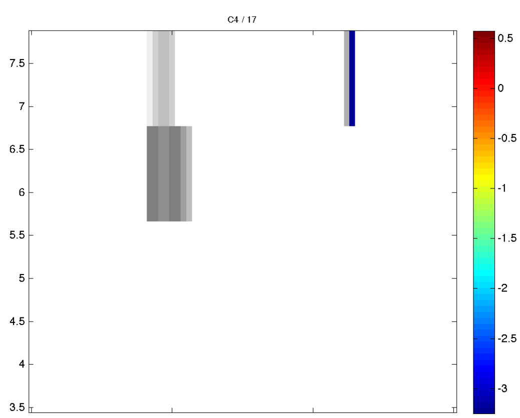


Figure 3.21: Thematic P600: Alpha band (8-12Hz) masked stats TFR

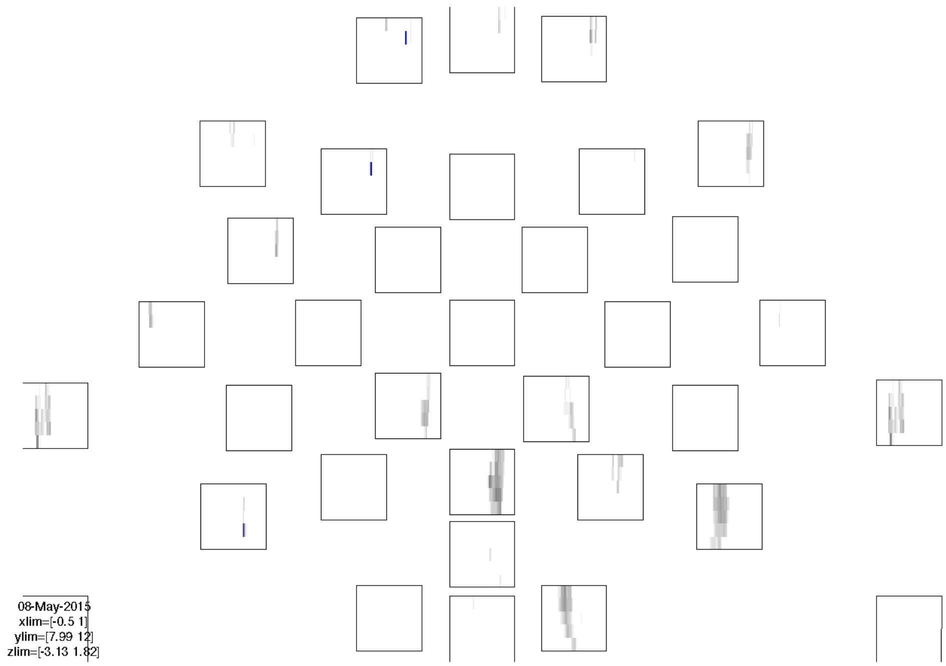


Figure 3.22: Thematic P600: Alpha band (8-12Hz) masked stats TFR, significant channels

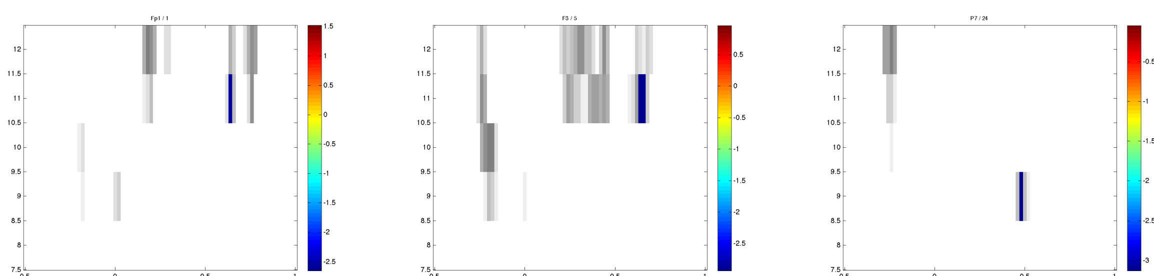


Figure 3.23: Thematic P600: Lower Beta band (13-20Hz) masked stats TFR

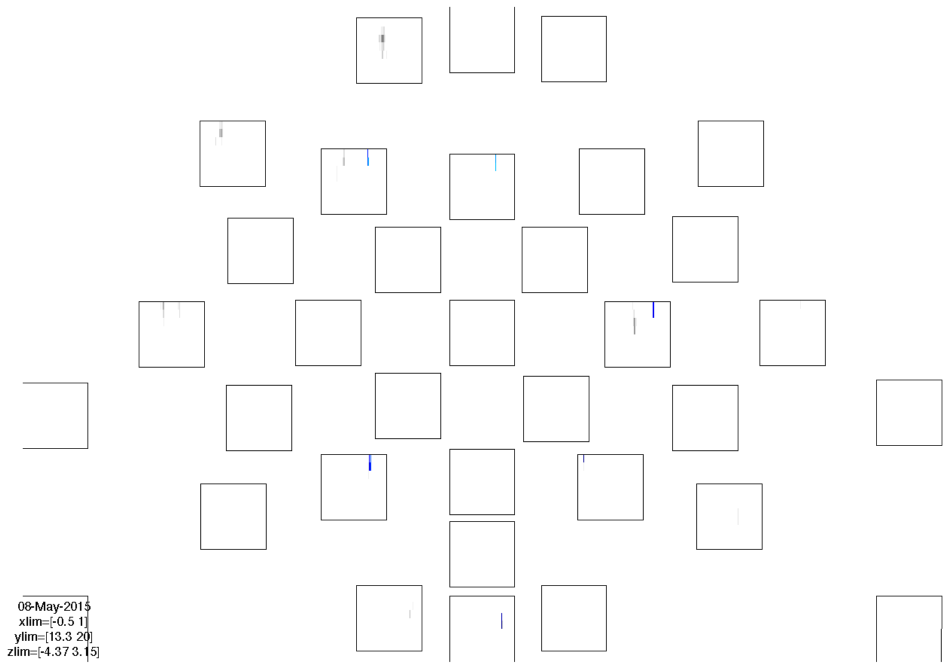


Figure 3.24: Thematic P600: Lower Beta band (13-20Hz) masked stats TFR, significant channels

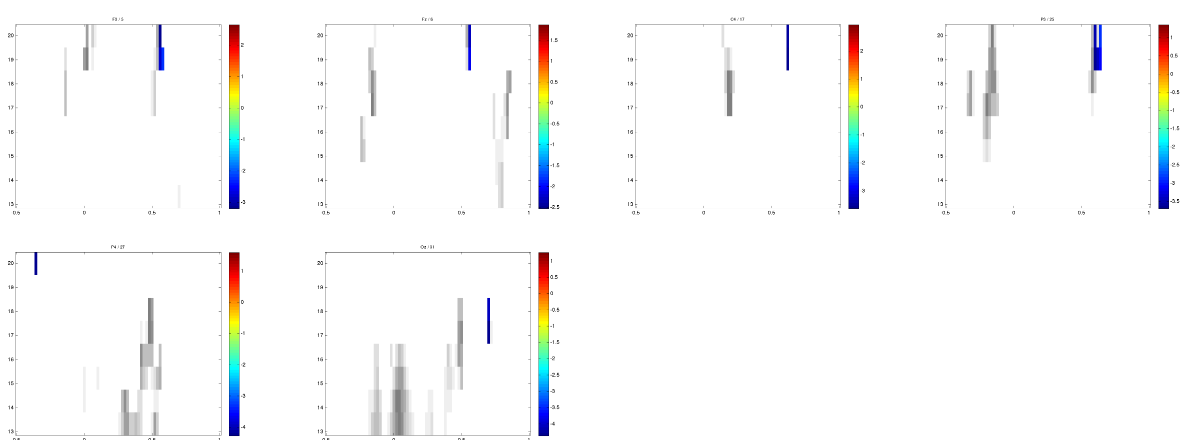


Figure 3.25: Thematic P600: Upper Beta band (21-30Hz) masked stats TFR

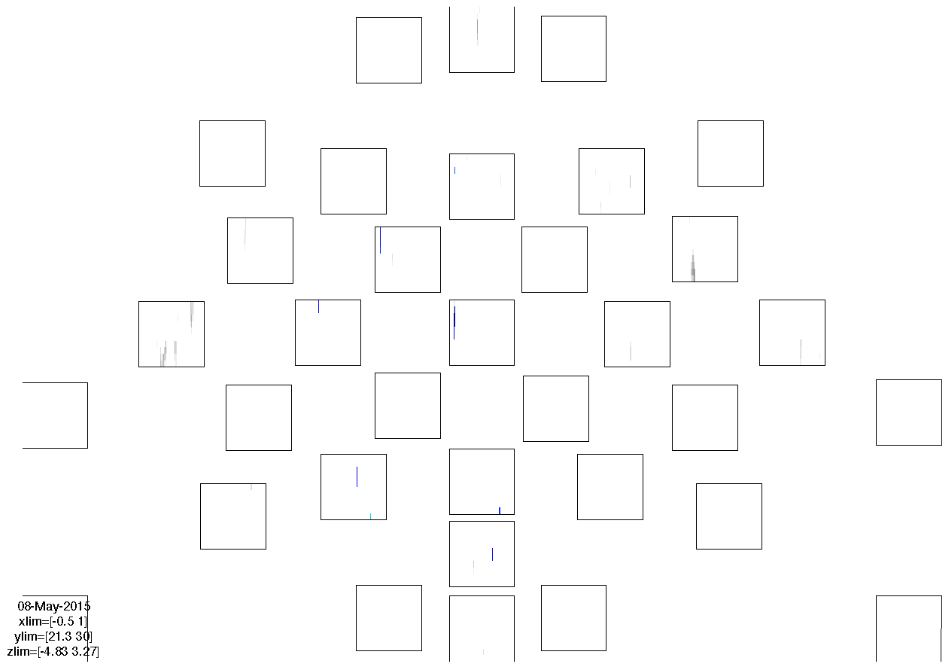
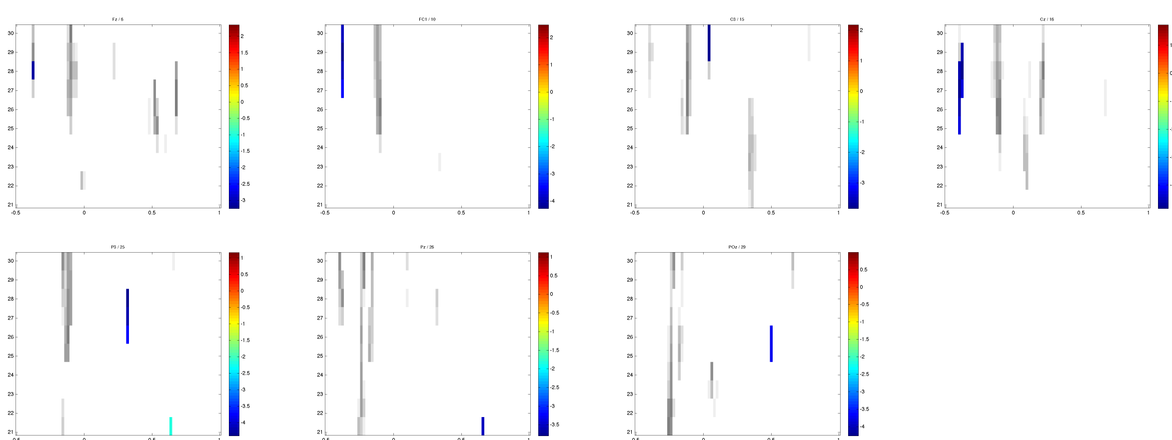


Figure 3.26: Thematic P600: Upper Beta band (21-30Hz) masked stats TFR, significant channels



Island Violations

ISC I wonder whether the candidate was annoyed *when* his son was questioned by one of his staff.
ISV I wonder who the candidate was annoyed *when* his son was questioned by.

ERPs

In a comparison of the Island Violation condition with the Island Control condition, there is a visible negative going deflection in left hemisphere activity from 400ms to 900ms, which is most widespread at 400-500ms and 800-900ms. T_{max} permutation tests reveal significant negative activity in left fronto-temporal channels at ∼425ms (Fig.).

Figure 3.27: Island Violation: ERPs

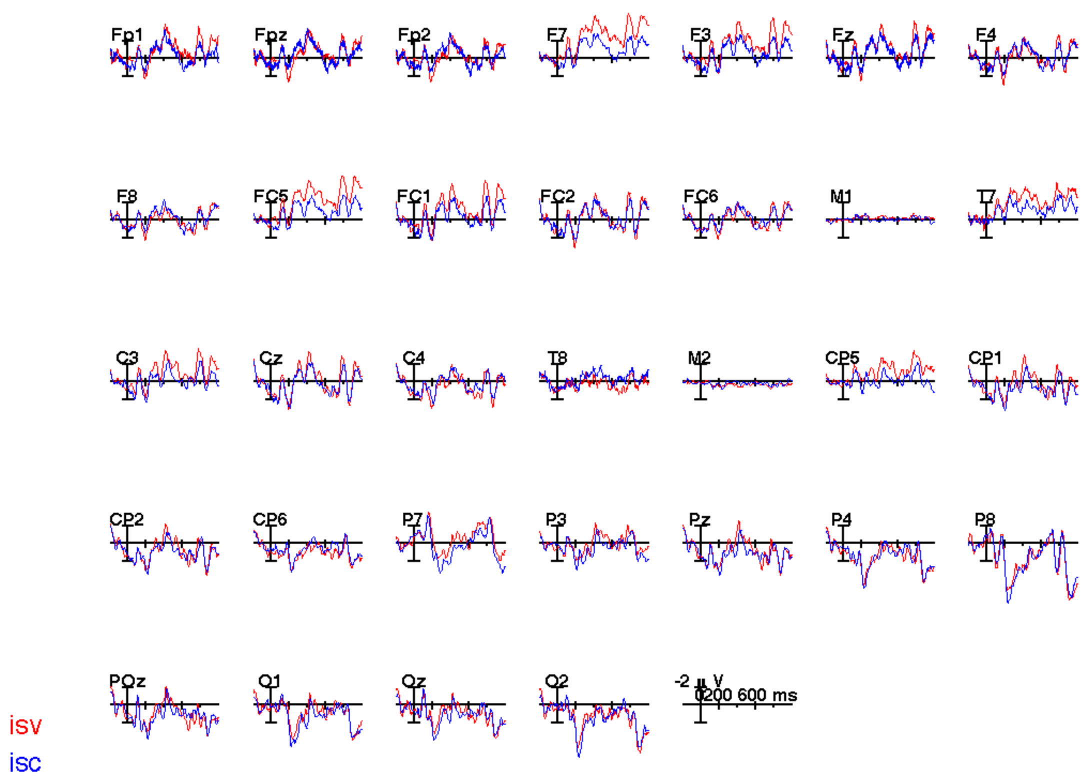
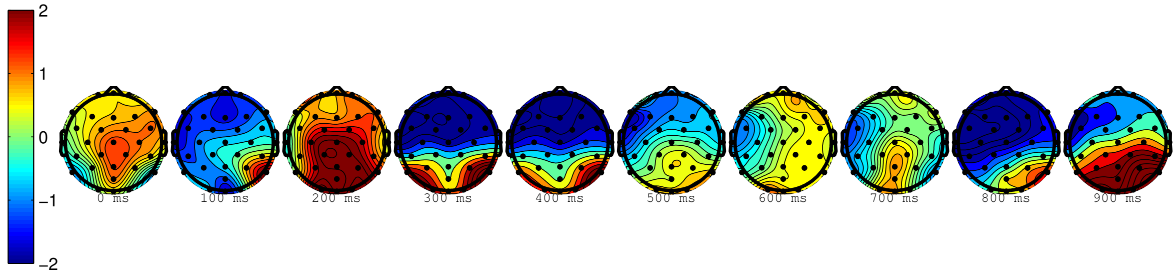
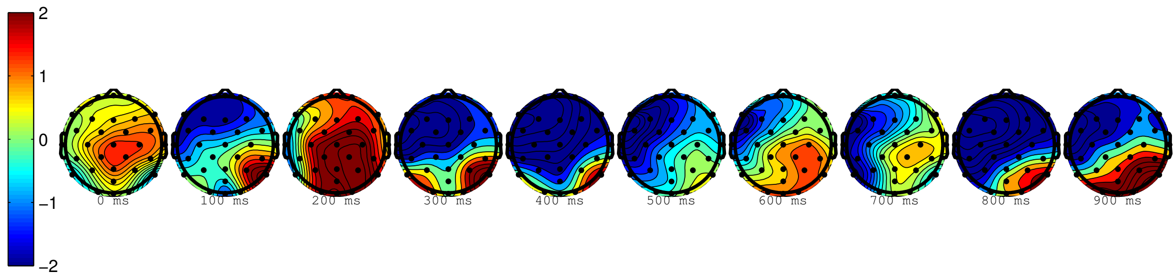


Figure 3.28: Island Violation: topoplots

Island Control



Island Violation



Difference plots

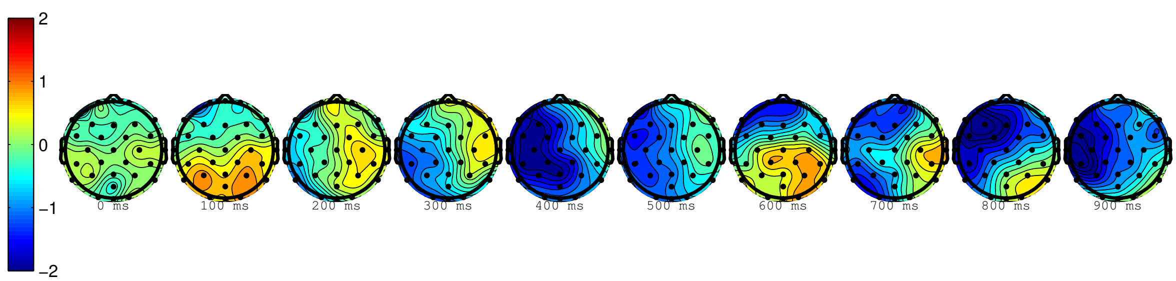


Figure 3.29: Island Violation: t_{max} permutation tests

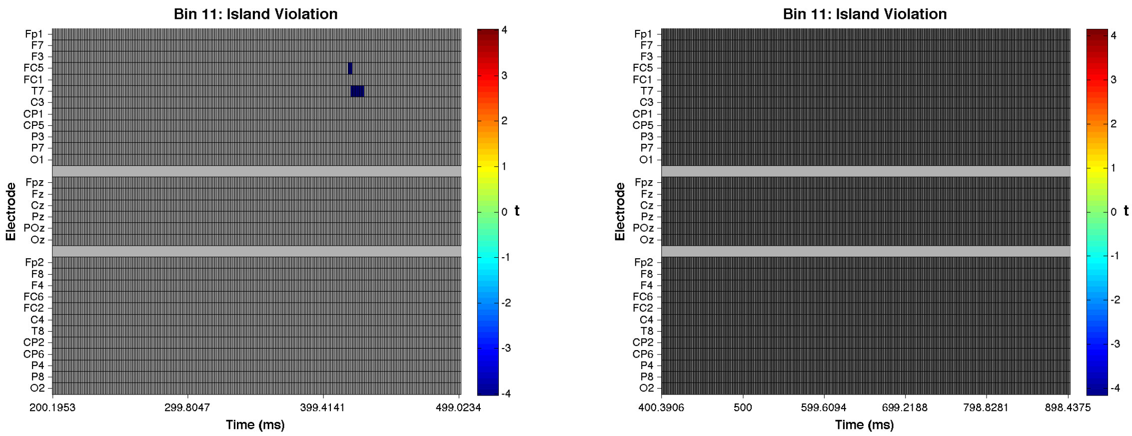


Figure 3.30: Island Violation: cluster mass permutation tests

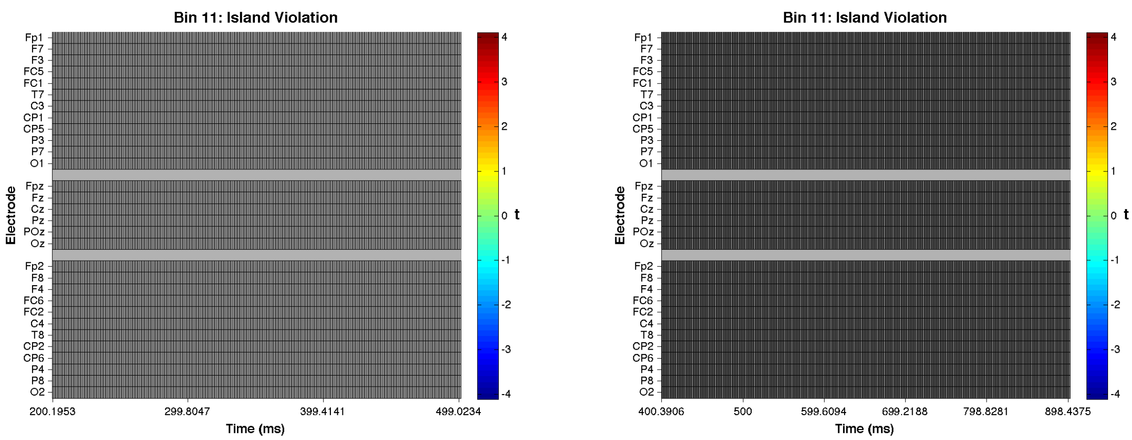
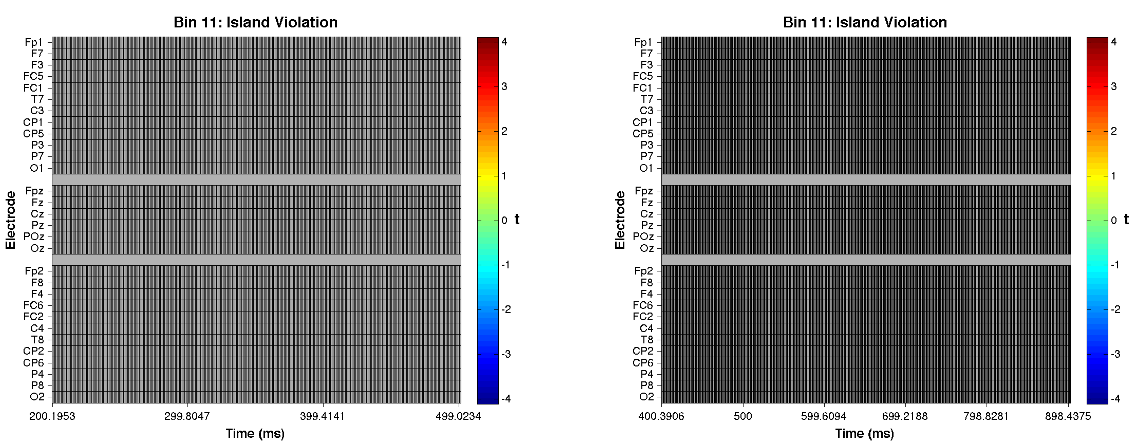


Figure 3.31: Island Violation: cluster mass permutation tests



TFRs

Comparing the Island Violation and Island Control conditions, there is a significant increase in Theta band activity (4Hz) between ∼200-250ms in central areas, and a decrease in Lower Beta activity (16Hz) at ∼300ms in left temporal areas.

Figure 3.32: Island Violation: TFR

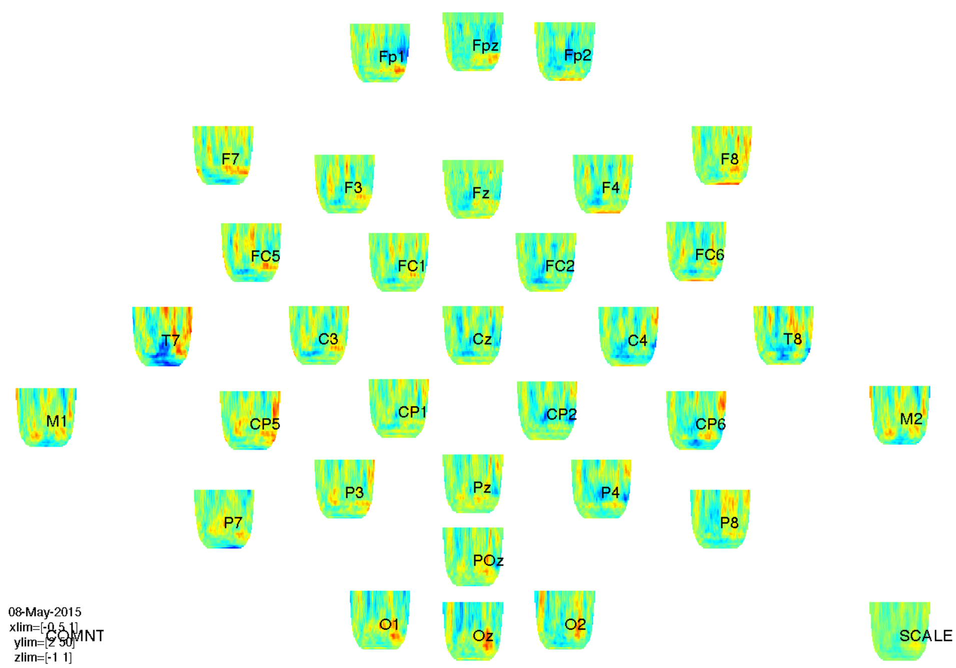


Figure 3.33: Island Violation: Theta band (4-7Hz) masked stats TFR

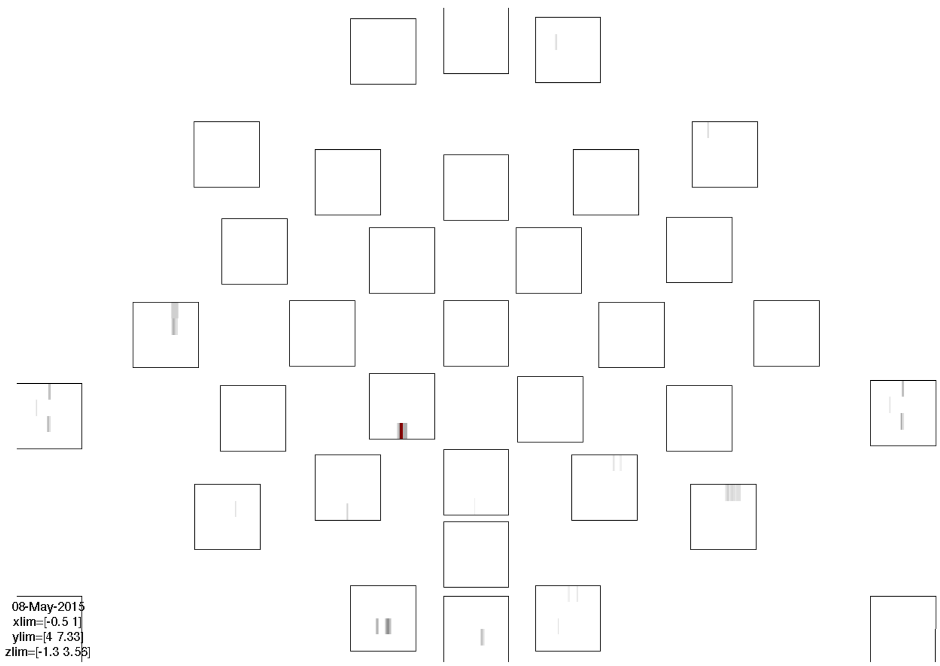


Figure 3.34: Island Violation: Theta band (4-7Hz) masked stats TFR, significant channels

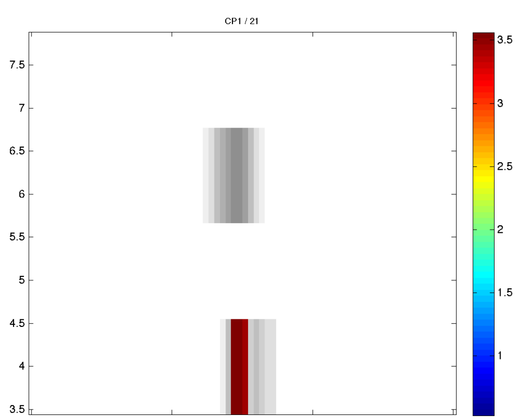


Figure 3.35: Island Violation: Lower Beta band (13-20Hz) masked stats TFR

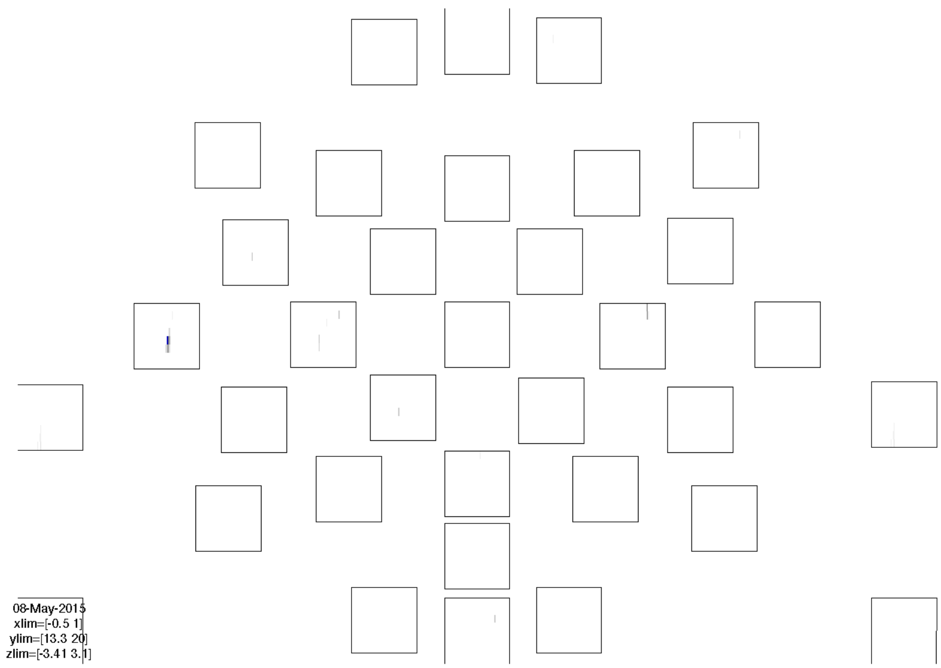
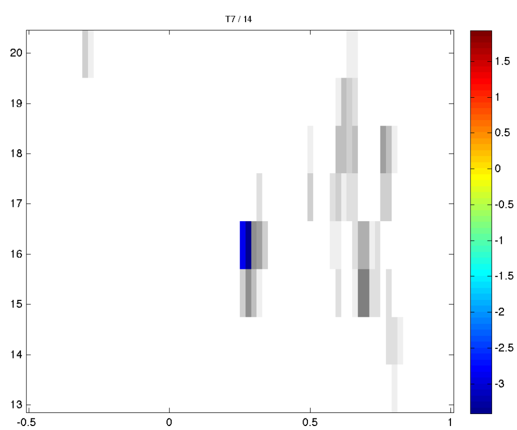


Figure 3.36: Island Violation: Lower Beta band (13-20Hz) masked stats TFR, significant channels



Phrase Structure Violations

PSC Jill heard that the students discussed Frank's *speech* about migrants.
PSV Jill heard that the students discussed Frank's *about* speech migrants.

ERPs

In a comparison of the Phrase Structure Violation condition with the Phrase Structure Control condition, there is a visible negative going deflection in prefrontal activity beginning at 400ms, which lasts until 900ms. These differences are not significant at any channel×time point.

Figure 3.37: Phrase Structure Violation: ERPs

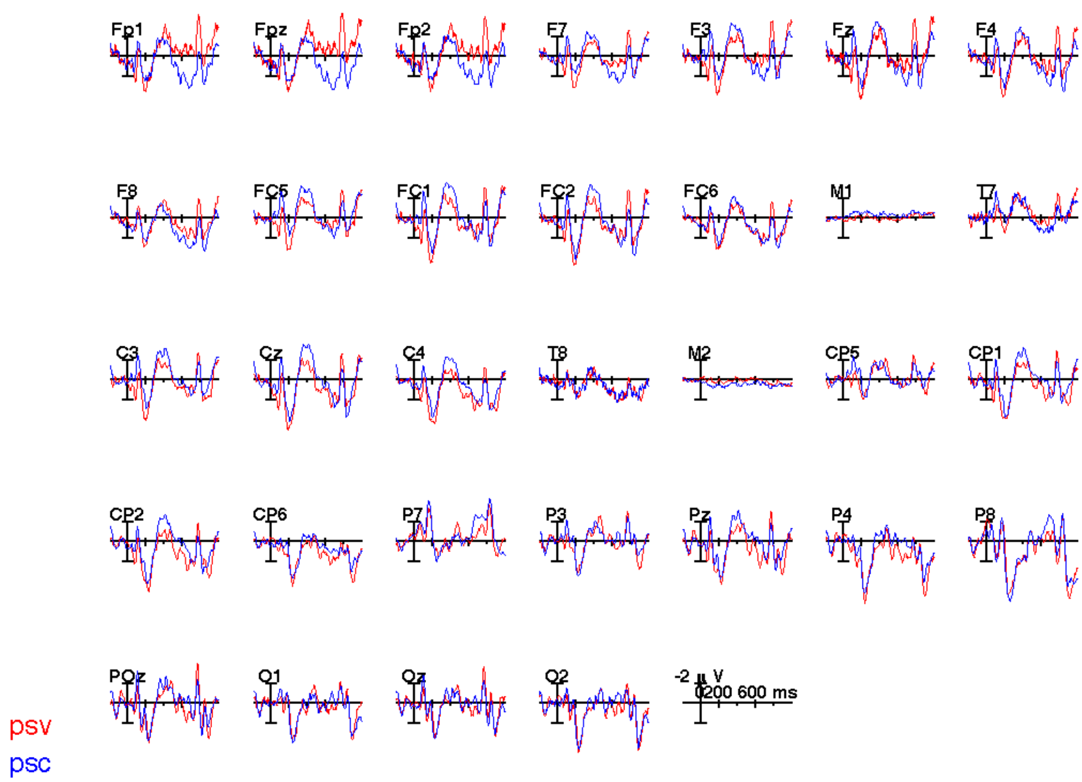
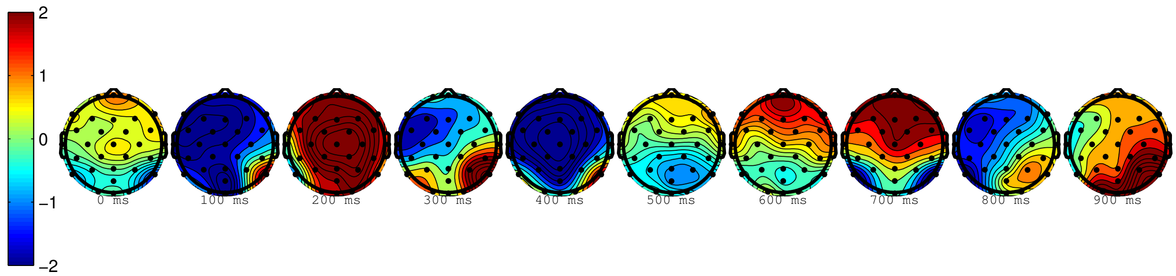
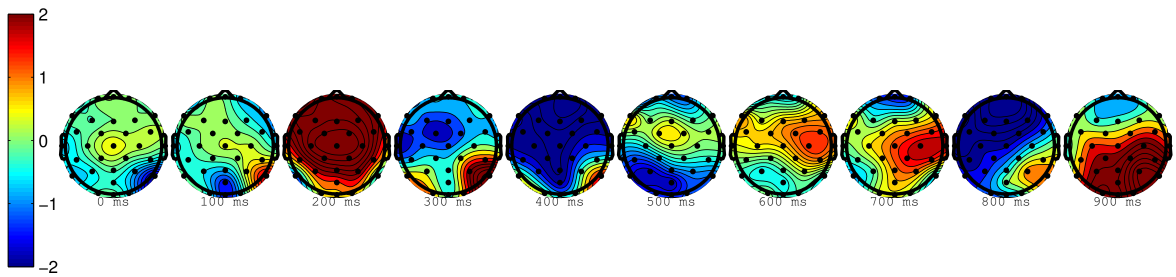


Figure 3.38: Phrase Structure Violation: topoplots

Phrase Structure Control



Phrase Structure Violation



Difference plots

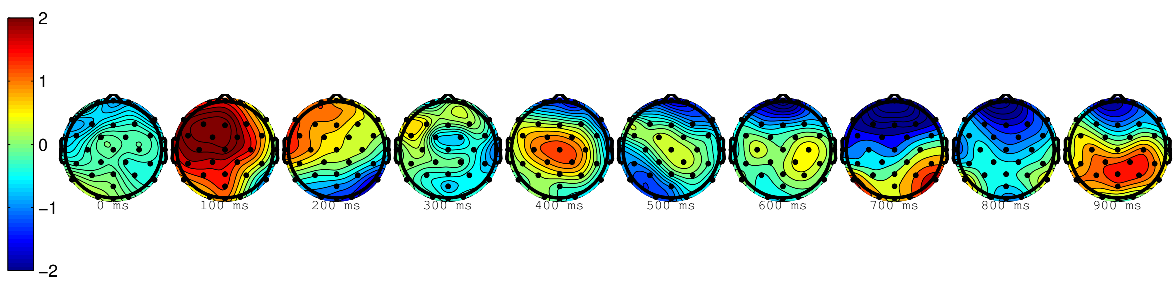
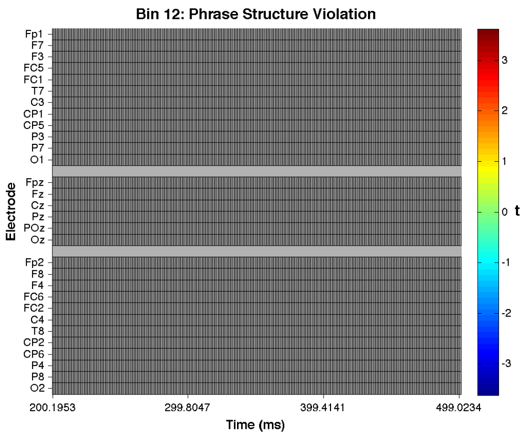


Figure 3.39: Phrase Structure Violation: t_{max} permutation tests



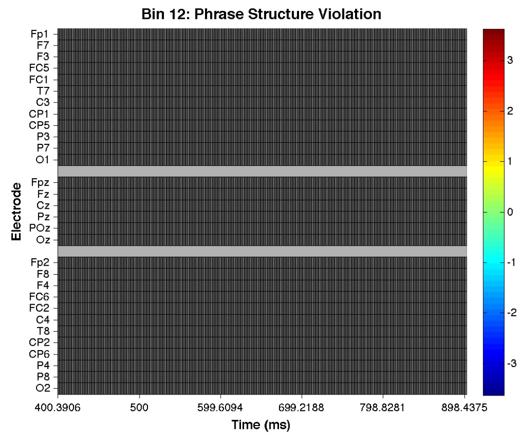
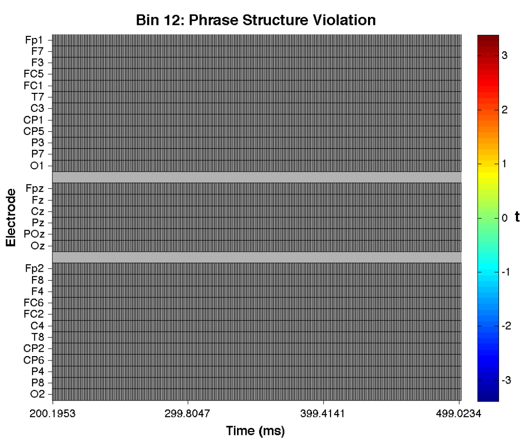
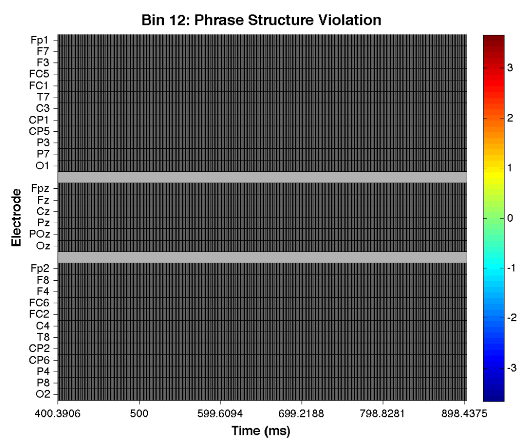


Figure 3.40: Phrase Structure Violation: cluster mass permutation tests

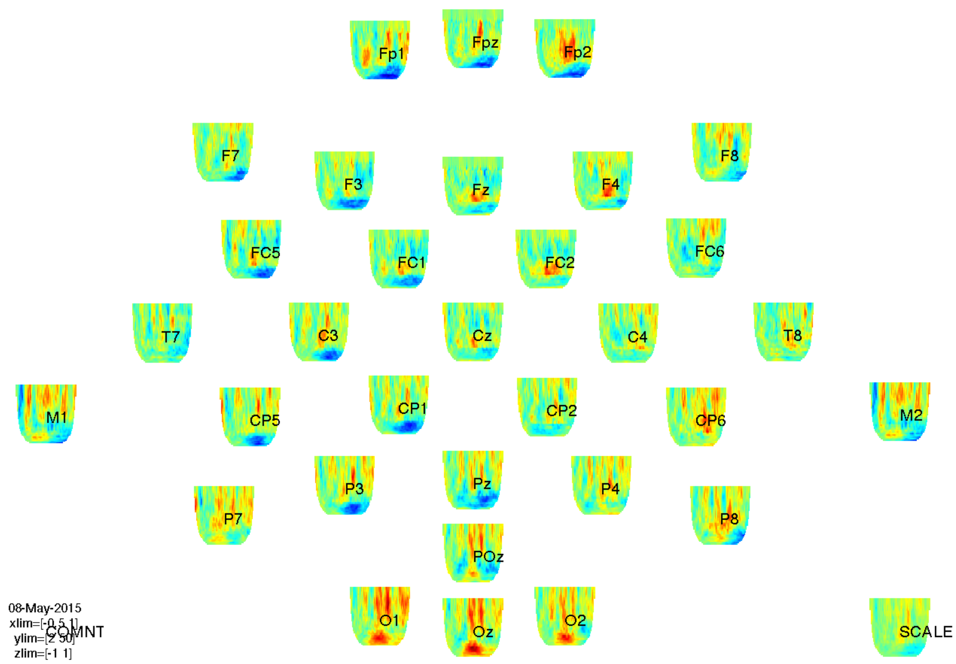




TFRs

Comparing the Phrase Structure Violation and Phrase Structure Control conditions, there are no significant differences in frequency activity at any channel×time point.

Figure 3.41: Phrase Structure Violation: TFR



3.3 Discussion

Overall, the results of this experiment do not find the late posterior positivities expected from these canonical P600 conditions. Rather, in most of the experimental conditions early negativities are found (akin to the LAN, or perhaps the N400), but the corresponding P600 is not present. This is likely a consequence of a flaw in the experimental design, in which stimulus sentences were split 50/50 between grammatical and (typically) P600-inducing sentences – which were either ungrammatical or anomalous. Work from Hahne & Friederici (1999) showed similar results of "missing" P600s, but in cases in which the P600 stimuli were in the majority (80%). Their work specifically sought to manipulate the probability of an anomalous event, in order to determine whether the P600 is tied to automatic processes (in which case it would occur under all designs) or to more controlled processes (in which case the design proportions may affect participants' strategy, and as a result their P600s). The authors found that P600s only occurred in cases in which the ungrammaticalities were the minority (in their case 20%). According to the authors, processes of repair/reanalysis which the P600 reflects will only be undertaken if they are a part of the reader/listener's parsing strategy, and this strategy may be changed to avoid such processes when they are being called upon a majority of the time.

While no hard-and-fast threshold exists for the P600, our design of 50% grammatical and 50% grammatical or anomalous appears to have affected subjects' parsing strategies such that no P600s are found. Much like Hahne & Friederici (1999), this work finds early negativities (in nearly every condition), which reflects the more automatic nature of those processes (though the LAN remains, as ever, elusive).

While the lack of P600s has pointed to a critical design flaw, this also offers the opportunity to examine the early negative effects in these ungrammatical/anomalous conditions, without any impedance from late positivities, which may otherwise have attenuated if not impeded the earlier activity.

		Garden Path						Thematic P600						Island Violation						Phrase Structure Violation					
		left		middle		right		left		middle		right		left		middle		right		left		middle		right	
		early	late	early	late	early	late	early	late	early	late	early	late	early	late	early	late	early	late	early	late	early	late	early	late
ERP	anterior									t				t											
cluster (default) tmax (t)	middle													t											
	posterior	t				t		t		t															
THETA	anterior																								
	middle																								
	posterior																								
ALPHA	anterior																								
	middle																								
	posterior																								
BETA	anterior	u u						u	l		l														
Lower (l) Upper (u)	middle						l						l	l											
	posterior			l l		l		u			u		l												
GAMMA	anterior																								
	middle																								
	posterior																								

Table 3.2: P600 Experiment: Amplitude (ERP) and Time-Frequency activity following syntactic reanalyses and violations.

Conditions representing violations-of-prediction/reanalyses

Table 3.3: P600 Experimental conditions: conditions representing violations-of-prediction/reanalyses

GPC	The woman heard that the broker intended *to* conceal the transaction at the meeting.
GPV	The woman heard that the broker persuaded *to* conceal the transaction was sent to jail.
THC	The woman suspected that the murder was *witnessed* by three bystanders.
THV	The woman suspected that the murder was *witnessing* the three bystanders.

In the "Thematic P600" condition, an embedded clause subject is inanimate (e.g., *the murder*) and is followed by a verb phrase in the active form (present progressive tense; e.g., *was witnessing*). In this condition, the critical word (the embedded verb: *witnessing*) represents a point at which assignment of thematic roles may need to be reevaluated, such that the embedded subject takes an Agent-role, rather than the Patient or Theme canonically associated with inanimate DPs[2].

In the Garden Path condition there is also a necessary reevaluation, in this case of the syntactic structure underlying the embedded subject DP and an embedded verb. In the Garden Path condition, the embedded verb (e.g., *persuaded*) is ambiguous between an active reading, in which it is the main verb of the embedded clause (e.g., *Molly hoped the broker persuaded her brother to cash out.*), and a passive relative clause version in which the verb represents the state of the embedded subject, which syntactically means it is the embedded verb of a passive relative clause whose complementizer and auxiliary verb have been omitted (e.g., *Molly hoped* [*the broker* [[who was] *persuaded to conceal the transaction*] $_{CP}$]$_{DP}$ *went to jail*).

ERPs

In the Garden Path and Thematic P600 conditions, there are significant, broad negative

[2]The critical point for the reevaluation is more specifically at the suffix of the verb, *ing*, which distinguishes the verb as active rather than passive (e.g., witness*ed*). However, since stimuli were presented visually (rather than auditorily), the point measured for the onset of critical processing is the onset of the entire word)

going deflections in amplitude activity in early time windows. In the Garden Path condition this negativity is significant in occipital channels bilaterally, and is marginally significant in anterior and posterior channels. In the Thematic P600 condition is biased to posterior channels, and has a later peak latency of ~400ms

TFRs

In both the Garden Path and Thematic P600 conditions, there are significant decreases in Alpha and Beta activity which occur between ~450-600ms in both cases, though with slightly different topographies.

In the Garden Path condition, Alpha decreases in occipital areas in early time windows, whereas in the Thematic P600 condition the decreases are slightly later, and extend to more frontal regions in the left hemisphere.

Decreases in Alpha activity likely signify an increase in the participant's attentional state following an anomaly (which provides evidence that the anomaly was is detected, despite the lack of P600).

In the Garden Path condition, Beta activity decreases in left anterior and right posterior areas in early time windows, and *increases* in later time windows (the early time windows of the subsequent word) in right occipital and parietal areas.

In the Thematic P600 condition, Beta activity decreases in left anterior and right posterior areas, across early and late time windows.

Event-related decreases in Beta activity in these conditions are consistent with the idea that the increases in Beta activity which occur throughout sentence processing (a reflection of successful sentence representation construction), can be disrupted, and these disruptions lead to relative decreases in activity. Furthermore, these decrease are consistent with the notion that Beta activity is sensitive to probabilities or expectations of items, rather than outright grammaticality. For example, while the Garden Path sentence is not an ungrammatical sentence, it is an unexpected construction, which sees a decrease in Beta activity as a result. In the Thematic P600 condition, the syntactic structure is not only grammatical but relatively canonical, however the pairing of thematic roles and syntactic structure is not. This is evidence against claims of an independent semantic analyzer which have been made in recent years based on exactly these types of sentences (Kuperberg et al., 2003).

The later increase in Beta activity in the Thematic P600 condition is curious, and appears to be a result of the activation of memory representations in response to an apparent gap. In this case, there are "gaps" following the obligatorily transitive verb (e.g., persuaded) when the Infl *to* is encountered instead of a DP, and there is a gap when the further embedded clause verb that follows Infl appears (e.g., *conceal*). These "gaps" are part of a more complicated syntactic reanalysis that must take place in the Garden Path condition, however these effects expressed in the early negativity are more automatic, and may well reflect a more narrow scope of evaluation.

These increases in Beta activity may perhaps reflect a more general disruption of a verb with its relations, given that they are also found following verb agreement errors in both Chapter 2 and Chapter 4.

In addition to these changes in Alpha and Beta activity, in the Thematic P600 condition there is an additional decrease in Theta band activity, which may represent the disruption to the construction of the sentence's semantic representation (Bastiaansen et al., 2008, 2010), and/or the lack of integration of the critical word (e.g., *witnessing*) into the existing representation. This change to Theta activity is not present in the Garden Path condition, which may reflect its nature as a more purely syntactic anomaly.

Conditions representing violations

In the metaphorically-named Island Violation (Ross, 1967), there is a dependency which

Table 3.4: P600 Experimental conditions: conditions representing violations

ISC	I wonder whether the candidate was annoyed *when* his son was questioned by one of his staff.
ISV	I wonder who the candidate was annoyed *when* his son was questioned by.
PSC	Jill heard that the students discussed Frank's *speech* about migrants.
PSV	Jill heard that the students discussed Frank's *about* speech migrants.

extends into an 'island,' or one of a list of syntactic structures which cannot support the presence of a gap. These structures have been identified as 'islands' for decades (Chomsky, 1965; Ross, 1967; Huang, 1982, etc.), though the explanation for their status remains debated to this day. Below is an exemplar list of the various known island types, reproduced from (Pearl & Sprouse, 2013):

a. *What did you make [the claim that Jack bought __]? (Complex Noun Phrase Constraint violation)

b. *What do you think [the joke about __] offended Jack? (subject island)

c. *What do you wonder [whether Jack bought __]? (whether island, or wh-island)

d. *What do you worry [if Jack buys __]? (adjunct island)

e. *What did you meet [the scientist who invented __]? (relative clause island)

f. *What did [that Jack wrote __] offend the editor? (sentential subject island)

g. *What did Jack buy [a book and __]? (coordinate structure)

h. *Which did Jack borrow [__ book]? (left-branch constraint violation)

In the Island Violation condition, ungrammaticality is caused by the existence of a gap within an *adjunct island*, signified by the occurrence of the *wh*-word *when* before the gap associated with the superordinate *wh*-word *who* has been resolved.

In the Phrase Structure Violation condition, a preposition (e.g., *about*) appears in a position where a Noun head is obligatory, specifically following a possessive Noun (e.g., *Frank's*).

ERPs

In the Island Violation condition, there is a significant early negativity in left anterior areas, akin to the LAN. In the Phrase Structure Violations, there is a visible, widespread negative deflection from ∼400-900ms, which is not statistically significant.

TFRs

In the Island Violation condition, there are significant increases in Theta band activity in left temporal areas, and significant decreases in Lower Beta activity, within early time windows.

This increase in Theta activity is consistent with the notion that a gap is automatically posited at the point of a clausal main verb, in accordance with the *Active Filler Strategy* (Frazier, 1987). This process requires utilization of working memory processes to activate the lexical-semantic properties of a filler to aid in the construction of a semantic representation of a sentence, processes which have been associated with Theta band activity previously (Bastiaansen et al., 2008, 2010).

In the case of the Island Violation, the gap that is posited at the critical word is illicit, which leads to a disruption of Beta activity in early time windows.

Oddly, no significant differences are found for the Phrase Structure Violation condition in this experiment. The reason for this result is unclear, as it includes overt morphological markers of an ungrammaticality, and therefore should trigger a response. Perhaps, given the lack of P600s in this dataset (discussed above), and the elusive nature of the LAN (discussed in Chapter 1), it is possible that both events simply did not occur. Or, perhaps the lack of response to this more local ungrammaticality is in comparison to the more syntactically/ semantically complex anomalies present in the other stimulus sentences.

Chapter 4

Gouvea P600: Ungrammaticalities, dependencies and Garden Paths

The author would like to give many thanks to Professor Ana Gouvea[1] *for sharing her data, and for allowing it be reanalyzed in this work.*

This data represents a reanalysis of published work authored by Gouvea et al. in 2009. In the work, there is a comparison of the amplitude response to (i) long-distance *wh*-dependencies, (ii) syntactic violations in the form of agreement violations between subject and verb, and (iii) garden path sentences, each of which have been associated in previous research with the P600 (e.g., Hagoort et al., 1993)

The authors characterize the P600 as a reflection of the assembly and disassembly of structural syntactic relations; they describe the latency of the P600 as a reflection of the time needed to retrieve those elements required for a given structural relation, and the amplitude and duration of the P600 as a reflection of the actual assembly (or disassembly) of the structural relation. Furthermore the authors describe topographical differences of the P600 as an

[1] Assistant Professor, Communication Sciences & Disorders Department, Florida International University

indication of different syntactic sub-processes in play.

In their case, the authors find a similar topography of the P600 response to sentences containing syntactic anomalies and garden path sentences, indicating similar underlying generators for both responses. The single exception is the *wh*-dependency condition, who's positivity has a more anterior distribution initially (∼300-500ms), before shifting to the more standard posterior distribution.

In terms of amplitude, the authors find a smaller P600 response following the *wh*-dependency, compared with the ungrammatical and garden path sentences.

In terms of latency the ungrammatical and garden path conditions differed (despite their similarity in scalp topography and duration). The ungrammatical condition had an additional early-mid (∼anterior) negativity, and a P600 onset between 500-700ms. On the other hand, the garden path condition had an earlier posterior positivity, whose onset was between 300-500ms.

The authors argue for an interpretation of the P600 in which its amplitude and duration reflect any structural operations which must take place (structure-building or destruction), and where the latency of the P600 onset is determined by the retrieval processes involved. These retrieval processes can be slowed in cases of more difficult integration (Kaan et al., 2000; Friederici et al., 2002), or in cases of longer dependencies (compared to shorter dependencies Phillips et al., 2005).

The reanalysis of this dataset in terms of its time-frequency representations offers yet another perspective on linguistically-distinct conditions, which may, as Gouvea et al. (2009) indicates, come from common underlying generators, or which may represent distinct responses that simply share in certain amplitude-domain characteristics. In addition, given that the results of The P600 Experiment (Chapter 3) did not find the P600 response expected, following errors similar to those examined here, this dataset provides an opportunity to compare P600 conditions whose amplitude and topography differ.

4.1 Methods (taken from Gouvea et al., 2009)

4.1.1 Participants

Twenty American undergraduate and graduate students of the University of Maryland, all of whom were native English speakers, participated in the experiment. The group was comprised of 8 women and 12 men, all of whom were between the ages of 19 and 28 (average age: 21.7 years). Of these 20 subjects, two were excluded as a result of recording artifacts (1 male, 1 female), leaving a remaining 18 participants. All subjects had normal or corrected-to-normal vision, and were strongly right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971). None had any known history of neurological impairment. Subjects provided written informed consent before the experiment, and were compensated financially for their participation.

4.1.2 Stimulus Materials and Experimental Design

The experimental materials consisted of 180 of quintuplets of English sentences (using 90 critical verbs), representing each of the five experimental conditions: (1) Control, (2) Ungrammatical Condition, (3) *Wh*-dependency, (4) Ungrammatical *Wh*-dependency, and (5) Garden Path sentences. In each of the conditions, the critical word was a ditransitive verb, functioning as the main verb of either a temporal modifier CP headed by *while* (Conditions 1 & 2), the main verb of an object-relative clause CP headed by *to whom* (Conditions 3 & 4), or the main verb of a coordinate CP(Condition 5), conjoined by *and*. In the Control *Wh*-dependency and Garden Path conditions, the verb appeared in past tense form (e.g., *showed*), while in the Ungrammatical conditions the verb was missing crucial verbal morphology (e.g., the suffix *-ed*) and appeared simply as the uninflected root form.

In the *Wh*-dependency condition, despite the fact that the critical ditransitive verb and the gap reflecting the dependency between it and the *wh*-phrase (representing the Dative Case PP, *to whom*) are not directly adjacent, previous has shown that the appearance of this verb triggers the construction and resolution of the dependency (Pickering & Barry, 1991; Phillips & Wagers, 2007). In the Garden Path condition, this verb represents the point at which it is realized that the sentence's syntactic structure must be reanalyzed, given the more commonly preferred analysis of conjoined DPs, rather than CPs, in accordance with the parsing principle of Minimal Attachment (e.g., *The patient met the doctor and the nurse with the white dress.* Frazier, 1987).

The choice of a ditransitive verb allowed for the greatest possible matching of the conditions, since the optional PP was either fronted or (grammatically) omitted. Furthermore, the use of the phrase *to whom* in the relative clause eliminates the case ambiguity present in other dependency conditions, and therefore further isolates processes of syntactic dependency construction from those of the case system.

With these 5 conditions, a set of five lists of 36 instances of each condition were created (180 unique items) using a Latin Square design. These items were then interspersed with 360 filler sentences, comparable in their structure and complexity, which resulted in a 2:1 ratio of fillers to targets. Items were divided into two trial sets of 270 sentences such that each list contained one instance of each of the 90 critical verbs. These trial sets were presented in two trial sessions, which were separated by at least two days. Target and filler stimuli were also pseudo-randomly organized prior to presentation.

Table 4.1: Gouvea P600 Experiment Conditions

CNTRL	The patient met the doctor while the nurse with the white dress *showed* the chart during the meeting.
UNGR	The patient met the doctor while the nurse with the white dress *show* the chart during the meeting.
WH-DEP	The patient met the doctor to whom the nurse with the white dress *showed* the chart during the meeting.
UNGRWH	The patient met the doctor to whom the nurse with the white dress *show* the chart during the meeting.
GP	The patient met the doctor and the nurse with the white dress *showed* the chart during the meeting.

4.1.3 Procedure

Participants, seated comfortable in a chair facing a computer screen, were visually presented sentences in an RSVP paradigm, with a stimulus-onset-asynchrony (SOA) of 500ms (300ms "on", 200ms "off"). Words were written in black on a white background. Trials first began with a fixation, and sentence stimuli were initiated by a button press by the subject. All sentences were followed by a yes/no comprehension question, with over feedback provided. Subjects were instructed to respond as quickly an accurately as they could, and to restrict eye blinks or other movement to periods in which the fixation was present (inter-trial intervals). Each experimental session was comprised of five, approximately 15 minutes blocks of 54 sentences, which were preceded by a practice session for familiarization with the procedure.

4.1.4 EEG recordings

EEG was recorded from 32 Ag/AgCl electrodes mounted in an electrode cap (Electrocap International) in a modified 10-20 configuration: (midline) Fz, FCz, Cz, CPz, Pz, Oz; (lateral) FP1/2, F3/4, F7/8, FC3/4, FT7/8, C3/4, T7/8, CP3/4, TP7/8, P4/5, P7/8, O1/2, and linked mastoids. EEG was recorded in reference to ground electrode AFZ, using a DC to 70 Hz low-pass filter. Data was re-referenced to linked mastoids for consistency with the literature. To monitor eye movements, two additional bipolar electrodes were placed on the right and left outer canthus, and above and below the left eye. EEG and EOG recordings were amplified and sampled at 500Hz, and impedances were kept below 5 kΩ per channel.

4.1.5 ERP Analysis

In Gouvea et al.'s ERP analysis, files were segmented into 11s intervals containing entire stimulus sentences, and trials with eye movement or other artifacts were rejected ($\sim 11\%$). Recordings were detrended to remove large, slow drift often found in DC recordings. Following this preprocessing, ERPs were calculated for each subject and each condition, in 1400ms time windows around the critical word (100ms baseline and 1300ms post-cw). Two types of repeated-measures ANOVAs were run using data from 18 channels representing six regions of interest according to two topographic factors: *laterality* and *anteriority/posteriority* (left anterior: FT7, F3, FC3; midline anterior: FZ, FCZ, CZ; right anterior: F4, FC4, FT8; left posterior: TP7, P3, CP3; midline posterior: PZ, CPZ, OZ; and right posterior: P4, CP4, TP8), in each of the six post-cw time-windows (0-300, 300-500, 500-700, 700-900, 900-1100, and 1100-1300ms). The first ANOVA included all conditions except the Garden Path, and was a 2x2 factorial design with the factors *grammaticality* and *wh-dependency*. The second ANOVA was a series of planned pairwise comparisons between the control and all other conditions. Follow-up ANOVAs were conducted where necessary, within specific topographic regions.

4.1.6 Time-Frequency Analysis

Note: Methods described here are identical to the methods described in Chapters 2 (Section 2.1.7) and 3 (Section 3.1.7), but are reproduced here for the convenience of the reader.

Time-frequency representations of the activity surrounding the critical word of each condition were created using the software package Fieldtrip (Oostenveld et al., 2011), on event epochs -500ms to 1000ms after the onset of the critical word. In a fashion somewhat similar to the preprocessing steps of the ERP analysis, epochs were extracted from the data, were baselined according to the average activity prior to the critical word onset, were detrended to remove any large, non-meaningful drifts in the data, and were rereferenced to the average of the two mastoid channels. Frequency activity within the window was then estimated in steps of 20ms, using a multitapered Fourier analysis approach with 'sliding' (and overlapping) Hanning windows.

In this type of analysis, a window containing a pure sine wave of a given frequency is convolved with the data for an estimate of the average activity at that frequency within the duration of the window. Windows of 5 cycles (5 wavelengths) were used to estimate activity in each frequency between 2 and 50 Hz, in 1 Hz steps. The length of the window was determined by the frequency being measured, which optimized the time×frequency trade-off in precision. With this approach, smaller windows could be used to estimate higher frequencies, increasing the temporal precision of the estimate. Furthermore, frequency window edges were smoothed in order to avoid edge effects in the estimates, by multiplying the frequency wave with an inverted cosine (the properties of which were a function of frequency as well). The result of this is a Hanning (Hann) window. Because tapering in the Hanning window necessarily means the loss of data at either edge of the window in each estimate, the estimates made using the window were overlapping (the window was successively 'slid' to the right, to an extent determined by the number of time points estimated for each frequency - here in steps of 20ms). This type of analysis has been used in similar existing work examining the brain's response to sentence processing (Bastiaansen & Hagoort, 2006, e.g.).

In this TF analysis, the baseline window was extended from the -200ms used in a typical ERP analysis to -500ms, to accommodate a minimum 2Hz frequency resolution of the baseline window. Furthermore, given that the smallest frequency activity examined statistically was 4Hz, this baseline window allowed for at least two wavelengths of each frequency in the baseline window (a standard preferred for our analysis).

Finally, the resulting TFRs were averaged for each subject to create a representation of changes in induced frequency activity for each subject (Tallon-Baudry & Bertrand, 1999a).

Subsequently, a statistical comparison of each condition was computed using the monte-carlo estimate of non-parametric significance probabilities (using permutation methods similar to those in the ERP analysis). In this case, in each statistical comparison the labels for each condition for each subject were randomly shuffled between conditions/subjects a large number of times, and each time a two-tailed dependent sample t-statistic and corresponding p-value were calculated, estimating the probability distribution for the null hypothesis.

The number of permutations used was determined as a function of the critical α value (here, 0.01), which was divided by the inverse of the number of comparisons (the number of channels$\times$frequencies$\times$time points) for each of five frequency bands. This number was multiplied by 1000, resulting in a number of permutations between 10,000 and 20,000.

4.2 Results

4.2.1 ERPs

In Gouvea et al. (2009)'s work, they find a posterior P600 in all experimental conditions, with fairly similar topographies, though with with different latencies and relative strengths. The authors find an early-onset (300-500ms) but otherwise canonical P600 response following the critical word in a sentence requiring reanalysis (Garden Path sentence), as well as a slightly later onset (500-700ms) but otherwise typical P600 following ungrammaticalities (verb-agreement error). The P600s in the ungrammatical conditions also show an early anterior negativity (LAN), which may in part explain the latency of the later positivity. Finally, the authors also find a P600 response at a clausal main verb which marks the initiation of the completion of a wh-dependency, however the response seen here was slightly different than that seen in the other two conditions. First, in the wh-dependency resolution condition, the positivity began early (300-500ms) in more anterior areas, before moving to the more canonical posterior regions. Furthermore, the P600 in this case was weaker than in the other conditions (only marginally significant in a 2x2 ANOVA). The authors explain this distinction in latency and relative strength as a result of the transparency of the case and thematic properties of the wh-phrase (*to whom*, dative case), which led to fewer structural relations needing to be constructed during processing. The authors propose the P600 is a reflection of both the number of structural relations created (amplitude), and the duration of those processes (latency). Therefore, fewer relations being created and a shorter duration of processing results in an earlier, lower-amplitude response.

4.2.2 TFRs

Ungrammaticality (Agreement Violation; -wh, +ungr) vs. Control (-wh, -ungr)

CNTRL The patient met the doctor while the nurse with the white dress *showed* the chart during the meeting.
UNGR The patient met the doctor while the nurse with the white dress *show* the chart during the meeting.

Comparing the Ungrammatical (Agreement Violation) and Control conditions, there is a significant increase in 9-11Hz in right prefrontal and left anterior areas between ∼0-150ms, a left midline, bilateral occipital and right posterior increases in 21(-25)Hz at ∼200ms, a right centro-parietal increase in 38-40Hz at ∼250ms, a bilateral midline and right occipital increase in 17/19-20Hz at ∼275ms, a left central decrease in 20Hz and a right parietal decrease in 24Hz at ∼600ms, and a right-lateralized central and parietal decreases in 15/17-18Hz (and 20Hz) at ∼750ms.

Overall, in the Ungrammatical (Agreement Violation) condition, Alpha activity (9-11Hz) increases in left anterior areas between ∼0-150ms after the onset of a Verb Agreement Violation, Lower Beta activity increases in bilateral midline and right occipital areas at ∼275ms, and decreases in left central areas at ∼600ms and in right-lateralized central and parietal areas at ∼750ms. Upper Beta activity increases in left midline, bilateral occipital and right

Figure 4.1: Ungrammatical vs. Control: Alpha band (8-12Hz) masked stats TFR

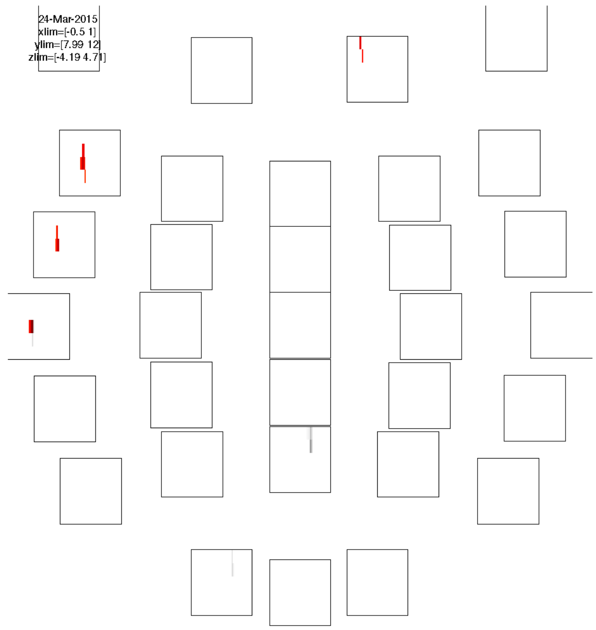
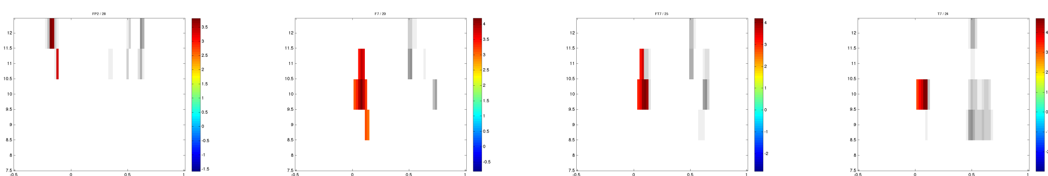


Figure 4.2: Ungrammatical vs. Control: Alpha band (8-12Hz) masked stats TFR, significant channels



posterior areas at ∼200ms, and decreases in right parietal areas at ∼600ms. Gamma activity increases in right centro-parietal areas at ∼250ms. In sum, there are early increases in Alpha, Beta and Gamma activity (widespread) followed by decreases in Beta activity.

Figure 4.3: Ungrammatical vs. Control: Lower Beta band (13-20Hz) masked stats TFR

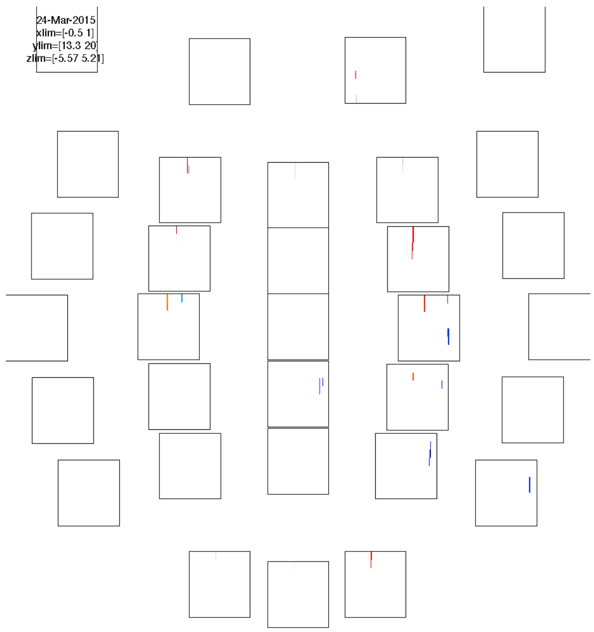


Figure 4.4: Ungrammatical vs. Control Condition: Lower Beta band (13-20Hz) masked stats TFR, significant channels

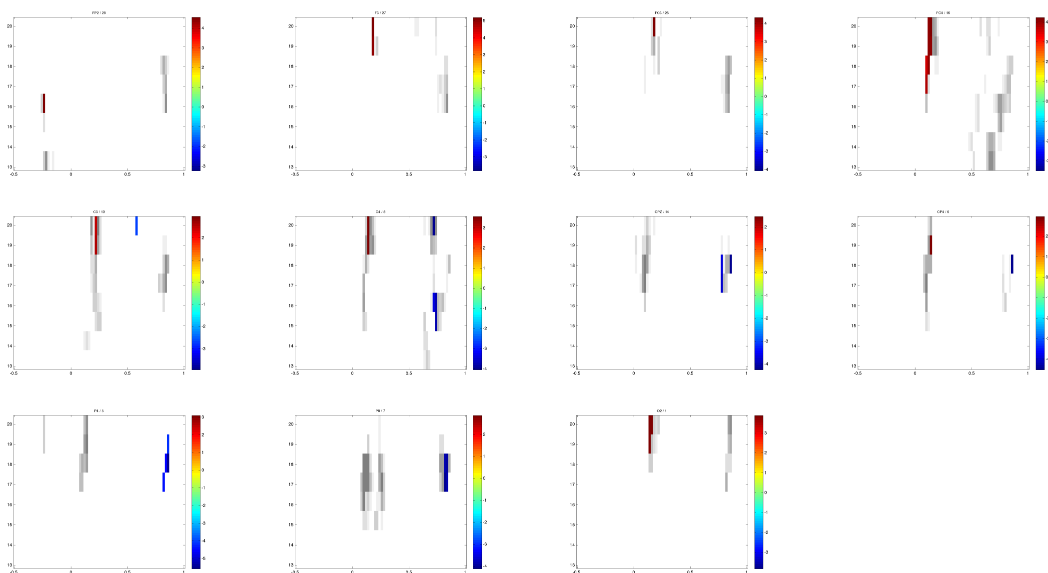


Figure 4.5: Ungrammatical vs. Control: Upper Beta band (21-30Hz) masked stats TFR

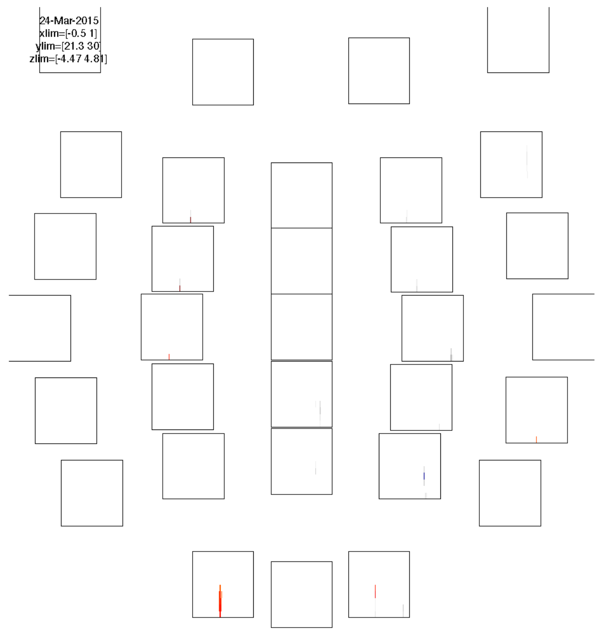


Figure 4.6: Ungrammatical vs. Control Condition: Upper Beta band (21-30Hz) masked stats TFR, significant channels

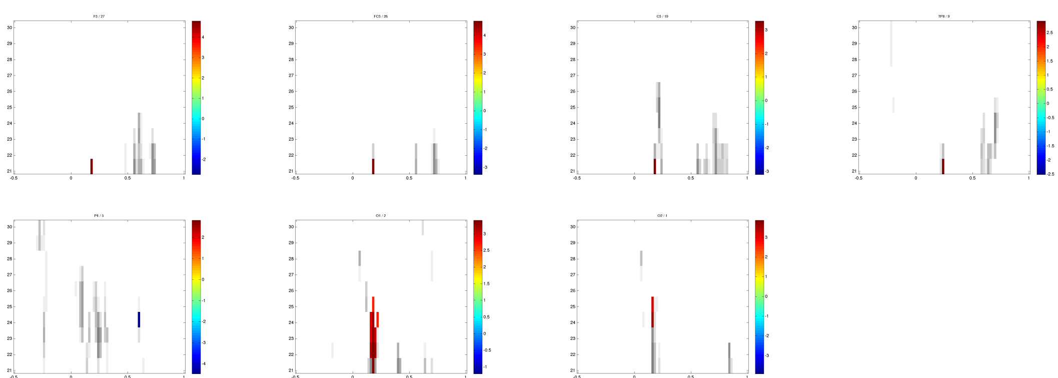


Figure 4.7: Ungrammatical vs. Control: Gamma band (31-40Hz) masked stats TFR

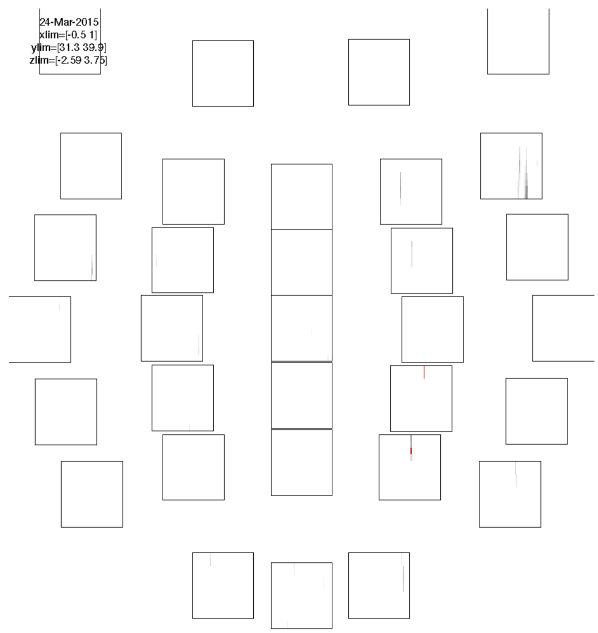
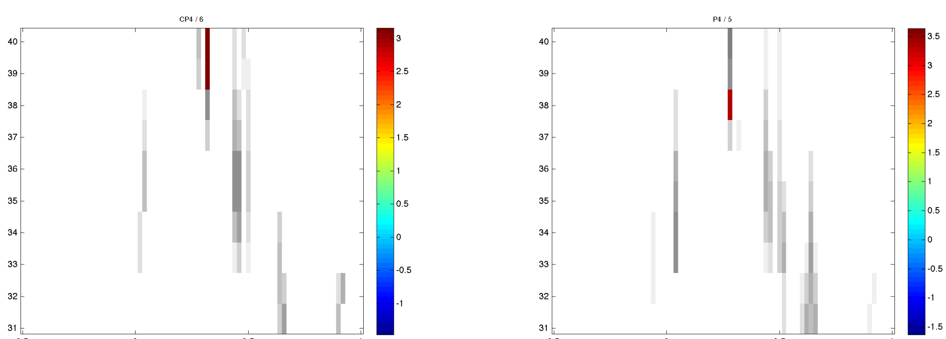


Figure 4.8: Ungrammatical vs. Control Condition: Gamma band (31-40Hz) masked stats TFR, significant channels



Wh-Dependency (+wh, -ungr) vs. Control (-wh, -ungr)

CNTRL	The patient met the doctor while the nurse with the white dress *showed* the chart during the meeting.
WH-DEP	The patient met the doctor to whom the nurse with the white dress *showed* the chart during the meeting.

Comparing the *Wh*-Dependency and Control conditions, there is a significant left anterior and left temporal increase in 10-12Hz from ∼-50-50ms, and there are several *pre*-cw increases, including in 19-22Hz in frontal areas, and in 34Hz in right temporal areas at ∼-450ms.

Overall, in the *Wh*-Dependency condition, Alpha activity increases just before and just after the *wh*-item, and there is a series of increases in Beta and Gamma activity in frontal and right temporal areas (respectively) at ∼-450ms.

Figure 4.9: Wh-Dependency vs. Control: Alpha band (8-12Hz) masked stats TFR

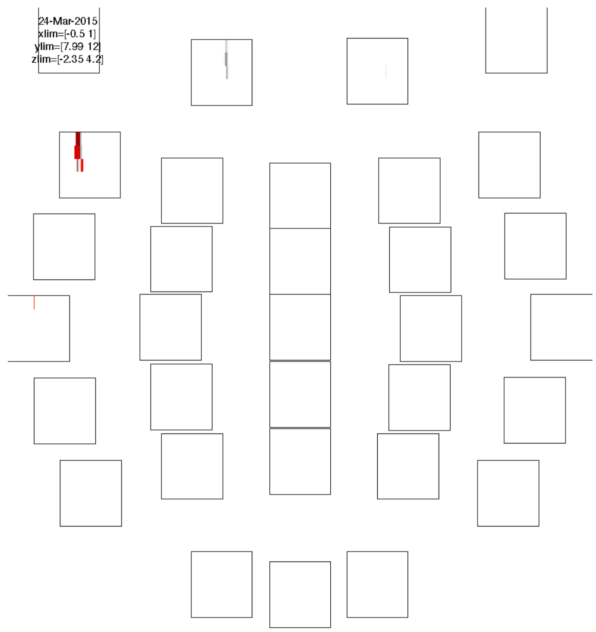


Figure 4.10: Wh-Dependency vs. Control Condition: Alpha band (8-12Hz) masked stats TFR, significant channels

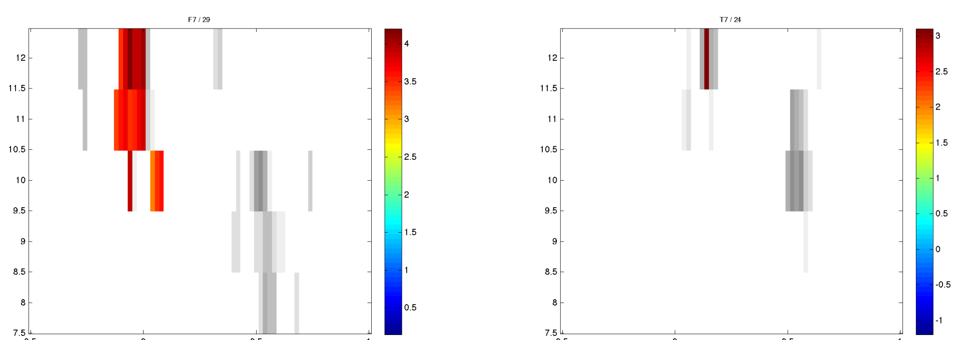


Figure 4.11: Wh-Dependency vs. Control: Lower Beta band (13-20Hz) masked stats TFR

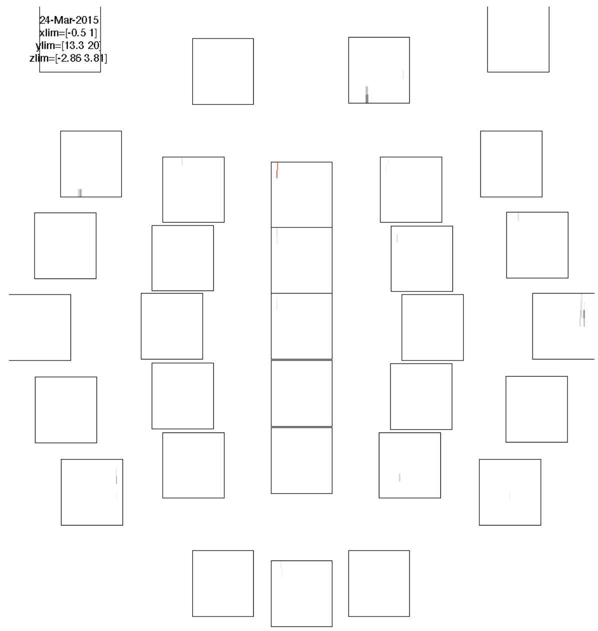


Figure 4.12: Wh-Dependency vs. Control Condition: Lower Beta band (13-20Hz) masked stats TFR, significant channels

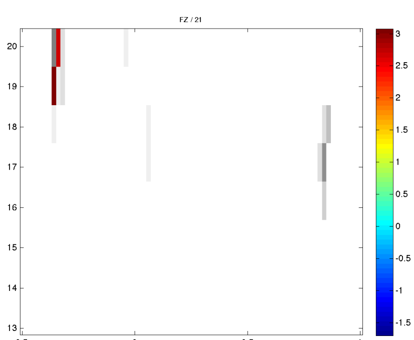


Figure 4.13: Wh-Dependency vs. Control: Upper Beta band (21-30Hz) masked stats TFR

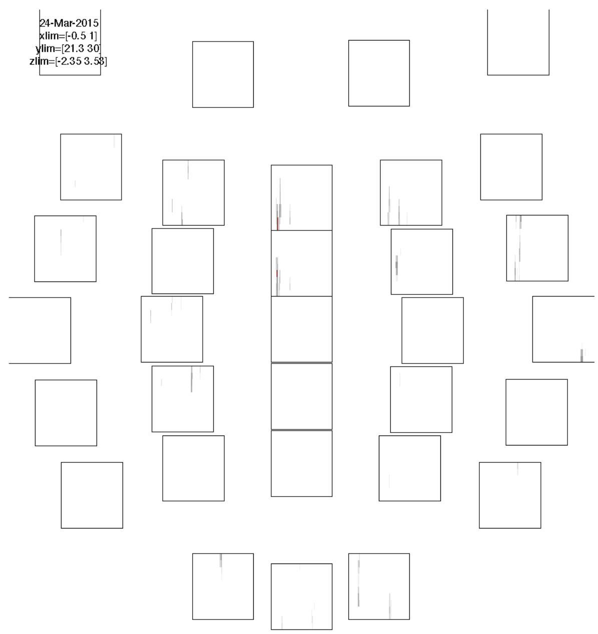


Figure 4.14: Wh-Dependency vs. Control Condition: Upper Beta band (21-30Hz) masked stats TFR, significant channels

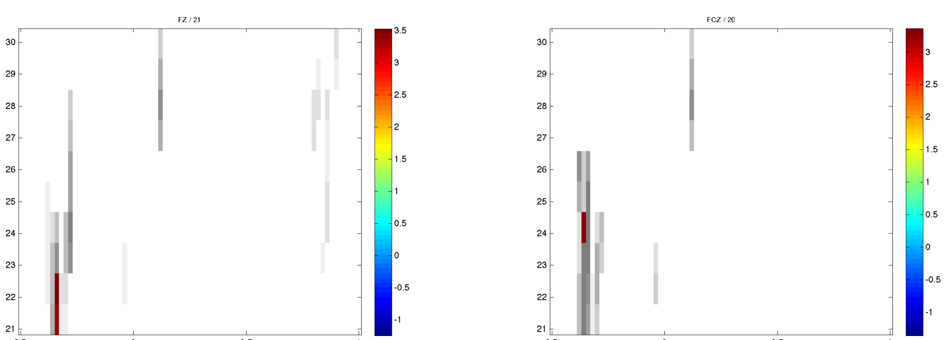


Figure 4.15: Wh-Dependency vs. Control: Gamma band (31-40Hz) masked stats TFR

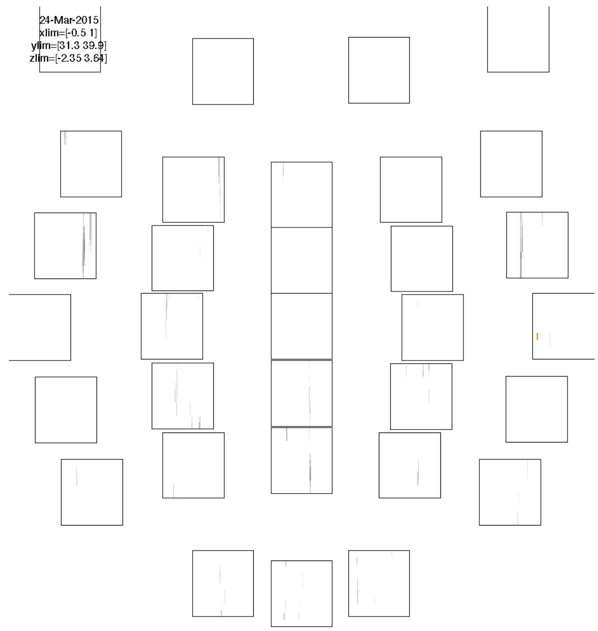
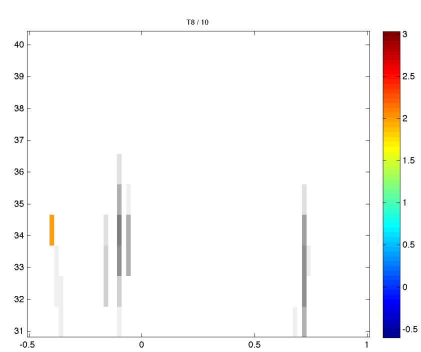


Figure 4.16: Wh-Dependency vs. Control Condition: Gamma band (31-40Hz) masked stats TFR, significant channels



Ungrammatical Wh-Dependency (+wh, +ungr) vs. Wh-Dependency (+wh, -ugr)

WH-DEP	The patient met the doctor to whom the nurse with the white dress *showed* the chart during the meeting.
UNGRWH	The patient met the doctor to whom the nurse with the white dress *show* the chart during the meeting.

Comparing the *Wh*-Dependency+Ungrammatical condition to the *Wh*-Dependency condition, there is a significant right frontal increase in 4Hz at ∼200ms, a left temporo-parietal increase in 7Hz at ∼200/250ms, a left central increase in 11-12Hz at ∼250ms, a left central and parietal increase in 14Hz at ∼300ms, a left frontal increase in 20Hz at ∼300ms, a left temporo-parietal increase in 7Hz at ∼350/400ms, a left temporo-parietal increase in 6Hz at ∼475ms.

Overall, in the *Wh*-Dependency+Ungrammatical condition, Theta activity increases in right frontal areas at ∼200ms (4Hz), in left temporo-parietal areas at ∼200/250ms (7Hz), an increase in left temporo-parietal areas at ∼350/400ms (7Hz), and in left temporo-parietal areas at ∼475ms (6Hz). Alpha band activity increases in left central areas at ∼250ms, Lower Beta band activity increases in left central and parietal areas at ∼300ms (14Hz), and Upper Beta activity increases in left frontal areas at ∼300ms (20Hz). In sum, Theta band activity increases in right anterior and left posterior areas from ∼200-475ms, and Alpha and Beta activity increases (widespread) between ∼250 and 300ms.

Figure 4.17: Ungrammatical Wh-Dependency vs. Wh-Dependency: Theta band (4-7Hz) masked stats TFR

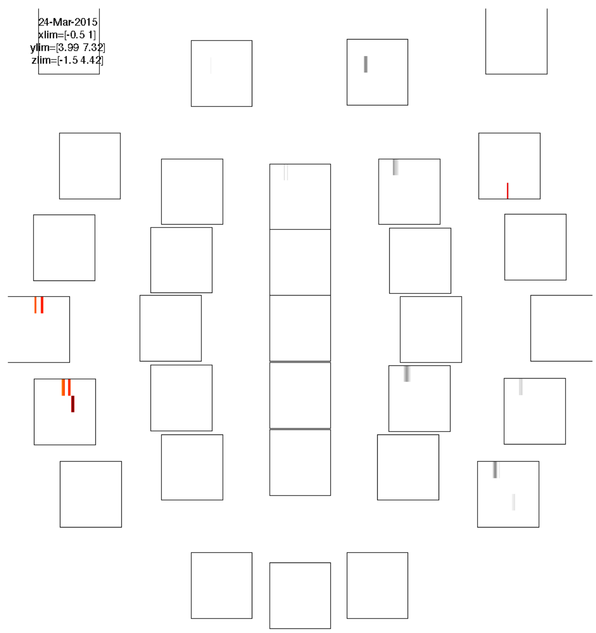


Figure 4.18: Ungrammatical Wh-Dependency vs. Wh-Dependency Condition: Theta band (4-7Hz) masked stats TFR, significant channels

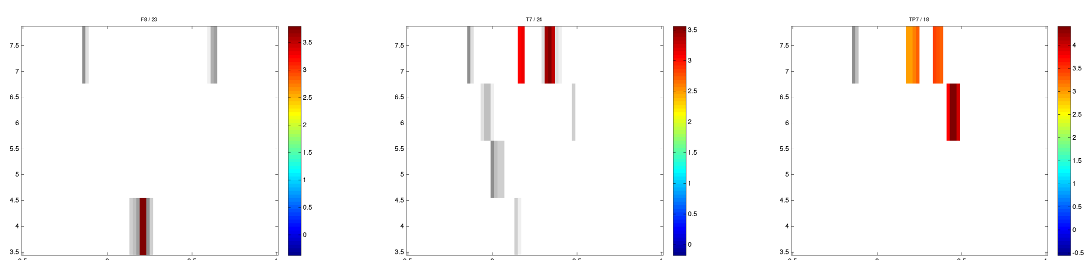


Figure 4.19: Ungrammatical Wh-Dependency vs. Wh-Dependency: Alpha band (8-12Hz) masked stats TFR

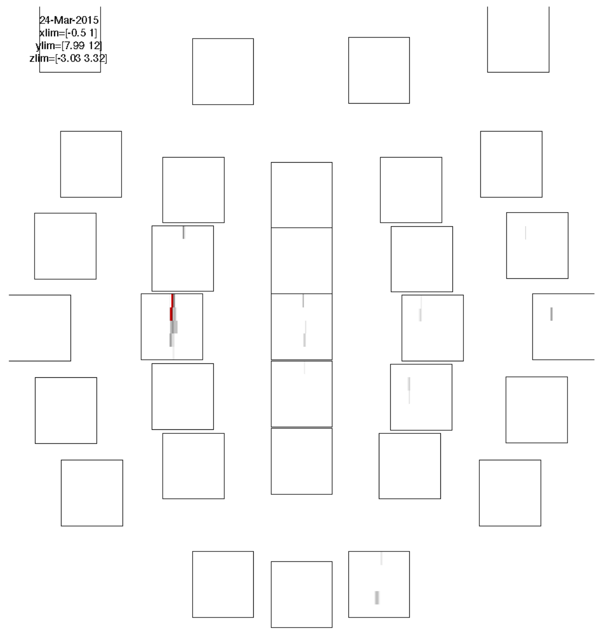


Figure 4.20: Ungrammatical Wh-Dependency vs. Wh-Dependency Condition: Alpha band (8-12Hz) masked stats TFR, significant channels

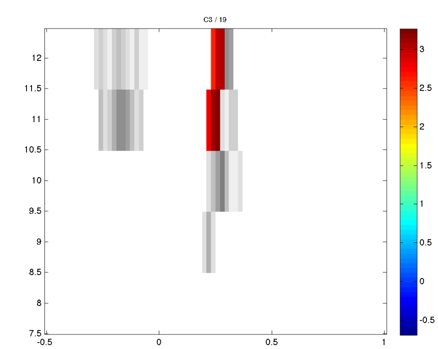


Figure 4.21: Ungrammatical Wh-Dependency vs. Wh-Dependency: Lower Beta band (13-20Hz) masked stats TFR

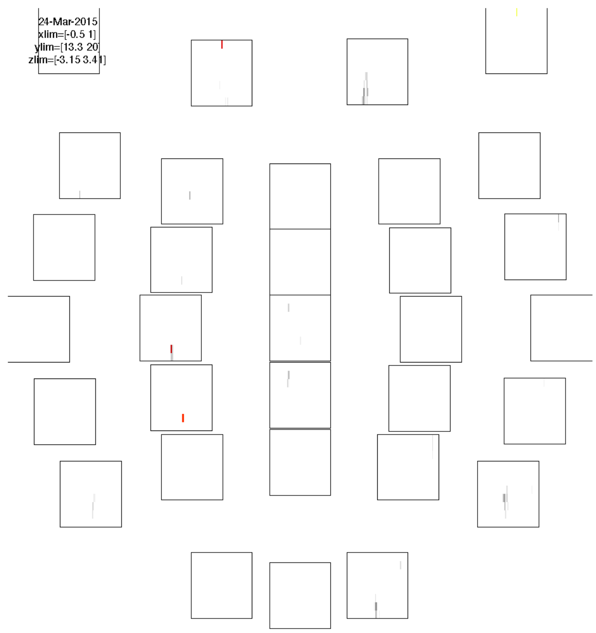


Figure 4.22: Ungrammatical Wh-Dependency vs. Wh-Dependency Condition: Lower Beta band (13-20Hz) masked stats TFR, significant channels

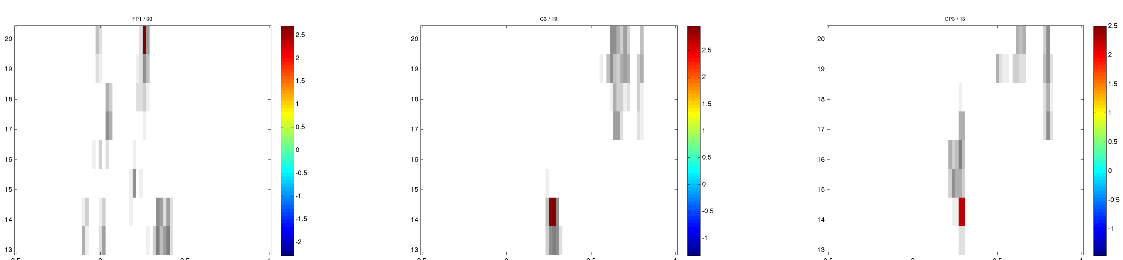


Figure 4.23: Ungrammatical Wh-Dependency vs. Wh-Dependency: Upper Beta band (21-30Hz) masked stats TFR

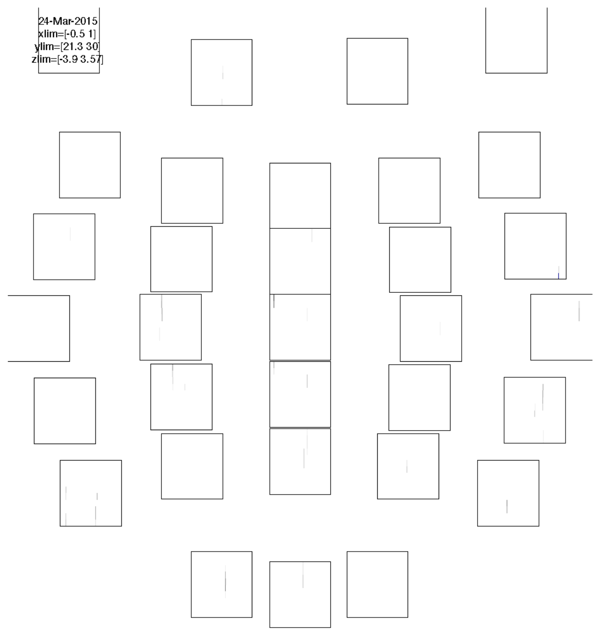
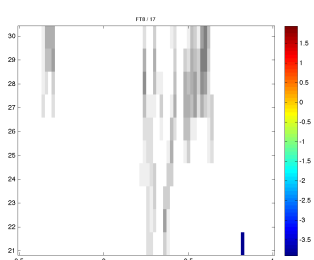


Figure 4.24: Ungrammatical Wh-Dependency vs. Wh-Dependency Condition: Upper Beta band (21-30Hz) masked stats TFR, significant channels



Ungrammatical Wh-Dependency (+wh, +ungr) vs. Ungrammatical (-wh, +ugr)

UNGR The patient met the doctor while the nurse with the white dress *show* the chart during the meeting.
UNGRWH The patient met the doctor to whom the nurse with the white dress *show* the chart during the meeting.

Comparing the *Wh*-Dependency+Ungrammatical condition to the Ungrammatical condition, there is a significant decrease in 16Hz in left centro-parietal areas at 0ms, an increase in 14Hz in parietal areas at ∼300ms, an increase in 5Hz activity in fronto-central areas at ∼475ms, an increase in 21-22Hz in (left) anterior areas at ∼475ms, an increase in 35Hz activity in left centro-parietal areas at ∼475ms, an increase in 20Hz activity in parietal areas at ∼500ms, an increase in 11Hz in left central areas at ∼750ms, an increase in 13-14Hz in left centro-parietal areas at ∼800ms,

Overall, in the *Wh*-Dependency+Ungrammatical condition, Theta activity increases in fronto-central areas at ∼475ms (5Hz), Alpha activity increases in left central areas at ∼750ms (11Hz), Lower Beta activity increases in parietal areas at ∼300ms (14Hz) and ∼500ms (20Hz), as well as in left centro-temporal ares at ∼800ms (13-14Hz), Upper Beta activity increases in (left) anterior areas at ∼475ms (21-22Hz), and Gamma increases in left centro-parietal areas at ∼475ms (35Hz).

Figure 4.25: Ungrammatical Wh-Dependency vs. Ungrammatical: Theta band (4-7Hz) masked stats TFR

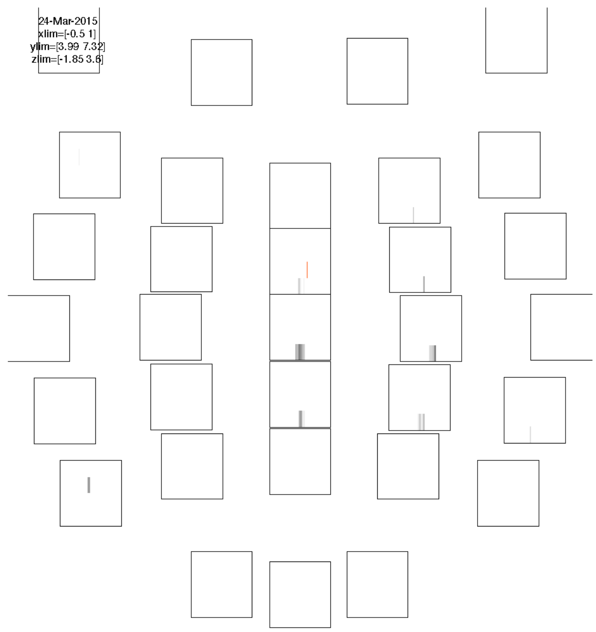


Figure 4.26: Ungrammatical Wh-Dependency vs. Ungrammatical Condition: Theta band (4-7Hz) masked stats TFR, significant channels

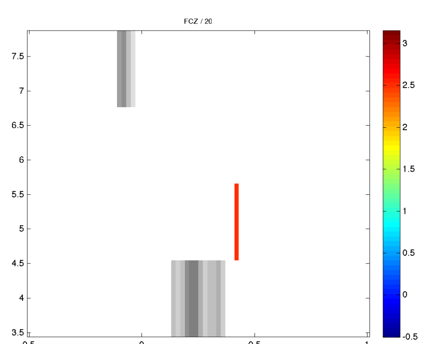


Figure 4.27: Ungrammatical Wh-Dependency vs. Ungrammatical: Alpha band (8-12Hz) masked stats TFR

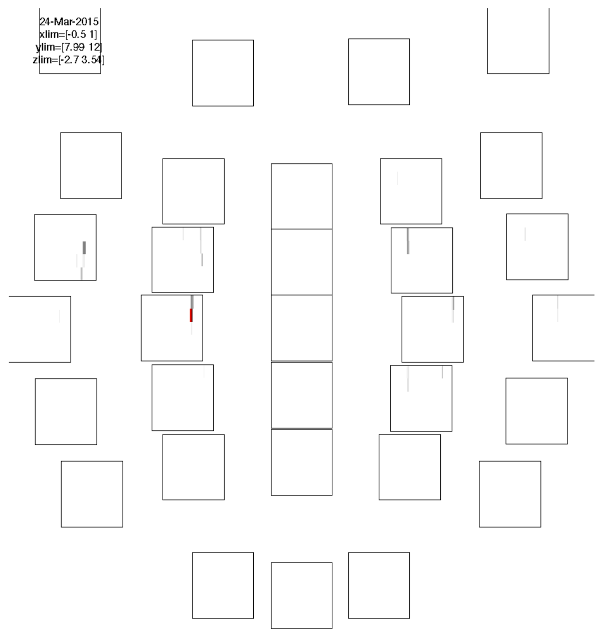


Figure 4.28: Ungrammatical Wh-Dependency vs. Ungrammatical Condition: Alpha band (8-12Hz) masked stats TFR, significant channels

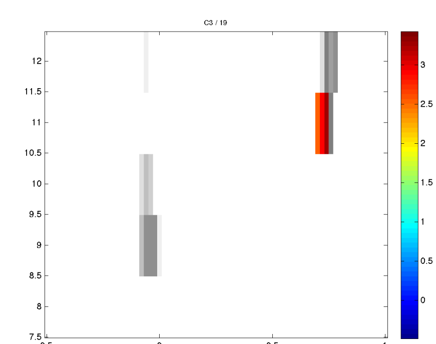


Figure 4.29: Ungrammatical Wh-Dependency vs. Ungrammatical: Lower Beta band (13-20Hz) masked stats TFR

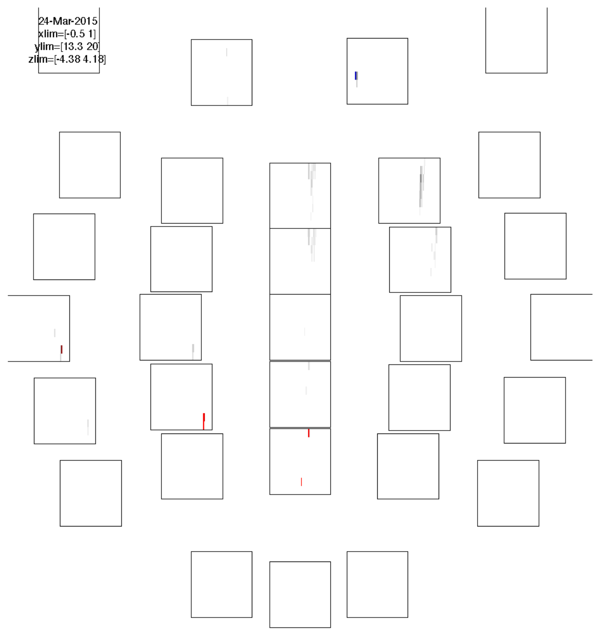


Figure 4.30: Ungrammatical Wh-Dependency vs. Ungrammatical Condition: Lower Beta band (13-20Hz) masked stats TFR, significant channels

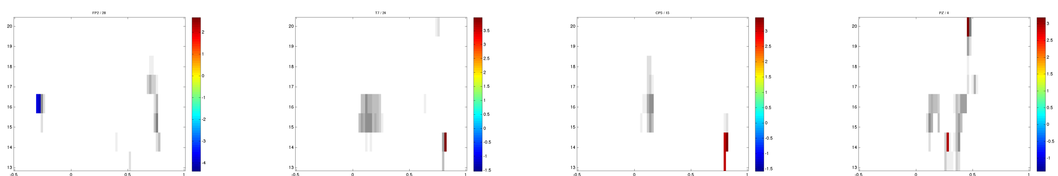


Figure 4.31: Ungrammatical Wh-Dependency vs. Ungrammatical: Upper Beta band (21-30Hz) masked stats TFR

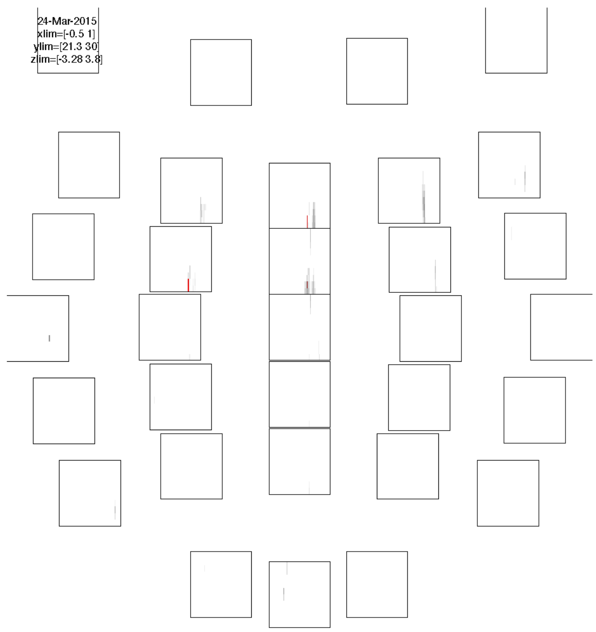


Figure 4.32: Ungrammatical Wh-Dependency vs. Ungrammatical Condition: Upper Beta band (21-30Hz) masked stats TFR, significant channels

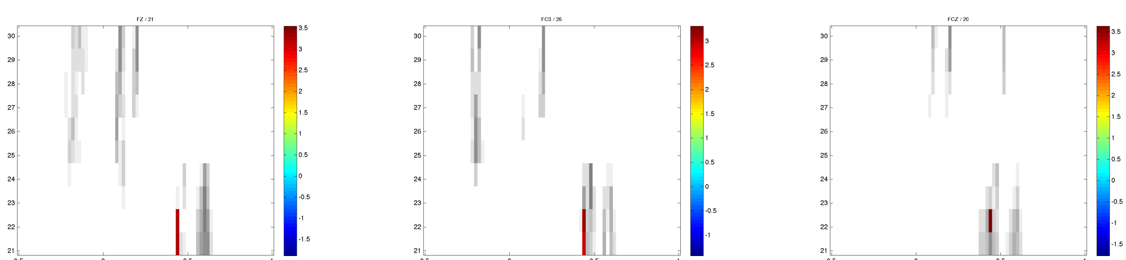


Figure 4.33: Ungrammatical Wh-Dependency vs. Ungrammatical: Gamma band (31-40Hz) masked stats TFR

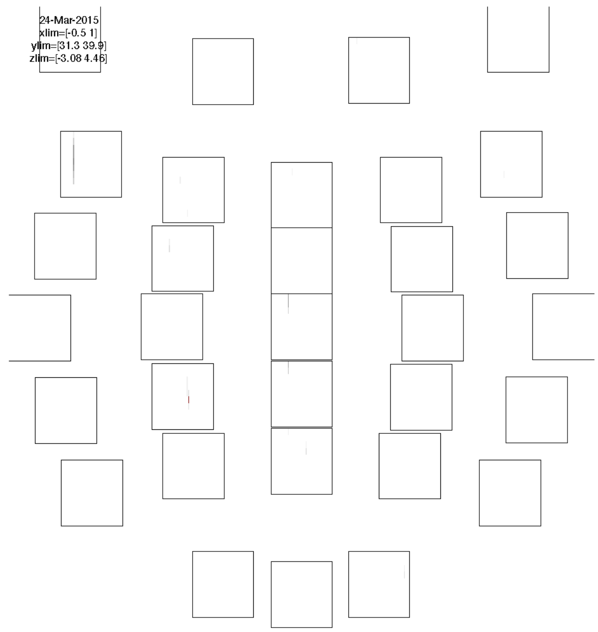
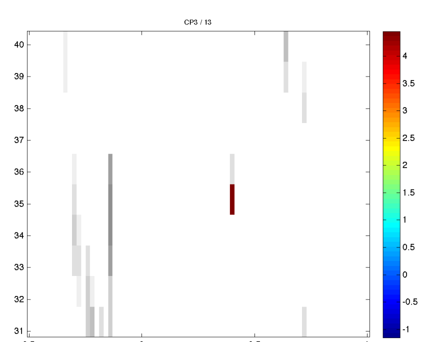


Figure 4.34: Ungrammatical Wh-Dependency vs. Ungrammatical Condition: Gamma band (31-40Hz) masked stats TFR, significant channels



Garden Path vs. Control (-wh, -ugr)

CNTRL The patient met the doctor while the nurse with the white dress *showed* the chart during the meeting.
GP The patient met the doctor and the nurse with the white dress *showed* the chart during the meeting.

Comparing the Garden Path condition to the Control condition, there is not significant activity at any frequency×time point.

4.3 Discussion

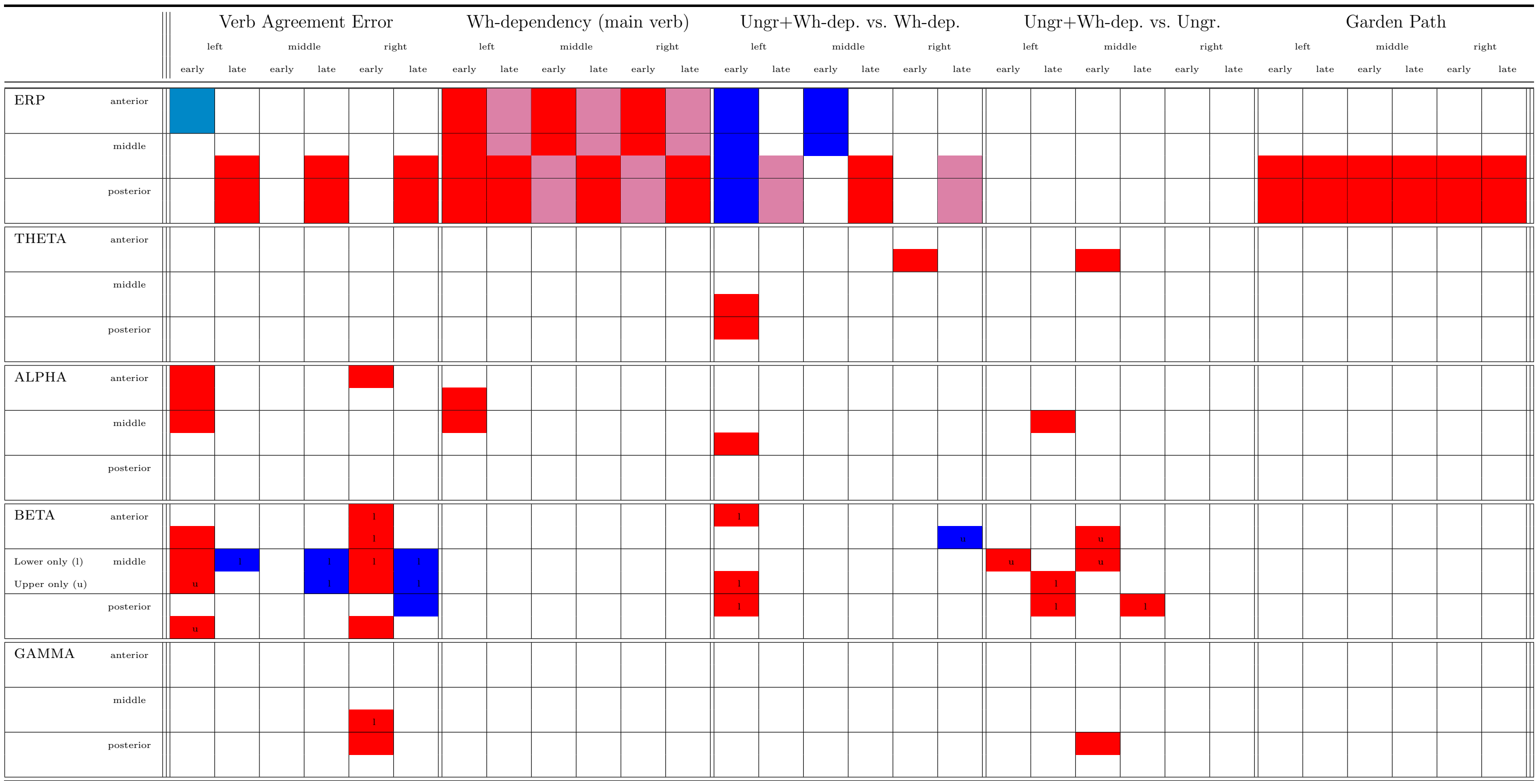


Table 4.2: Gouvea data: Amplitude (ERP) and Time-Frequency activity following *wh*-dependency resolution, ungrammaticalities and syntactic reanalyses.

4.3.1 Ungrammaticalities

ERPs

In the Ungrammatical condition, in which an agreement error is present on a clausal main verb, there is a marginally significant early anterior negativity, akin to the LAN. This negativity is followed by a late posterior positivity, akin to the P600.

In the Ungrammatical+Wh-dependency condition, when compared to the Wh-dependency condition there is a significant early broad negativity, which is primarily left-lateralized, akin to the LAN. This is followed by a significant yet slightly weaker posterior positivity in later time windows (the positivity is only marginally significant outside of the midline channels), akin to the P600.

TFRs

Ungrammaticalities on the whole are followed by early increases in Theta, Alpha, Beta, and Gamma frequencies, with differences in particular frequency composition and latency depending on the ungrammaticality also represents the point of a *wh*-dependency resolution, and by late decreases in Beta activity.

In cases of an ungrammaticality alone (no *wh*-dependency), significant increases in Alpha, Beta and Gamma activity appear immediately at the onset of the critical word, and last throughout much of early time windows. These increases are then followed by decreases in Beta activity in left anterior and right posterior areas in late time windows.

When a *wh*-dependency is also present (as in the Ungrammatical+Wh-Dependency condition), compared to a *wh*-dependency alone, there are increases in (primarily left hemisphere) Theta, Alpha and Beta activity, in early time windows, which are a bit delayed relative to the Ungrammatical condition. In this case, such increases are followed by decreases in Beta activity in right anterior areas in late time windows.

Increases in (Theta, Gamma), Alpha and Beta activity in the ungrammatical conditions are similar to those seen in the Verb Agreement Violation condition of Chapter 2, and following the gap of the Long-distance Dependency condition of Chapter 2. These increases may be the result of an attempt to integrate the ungrammatical main verb or its missing verbal argument (gap) into the larger sentential representation under conditions of uncertainty (Davidson & Indefrey, 2007). Increases in Beta activity may reflect the maintenance of current representations while previous representations are activated in the attempt to update the (disrupted) thematic representation.

The late time-window decreases in Beta activity are similar to those seen following morphosyntactic violations in Chapter 2, Island Violations in Chapter 3 and in responses to conditions requiring *reanalysis* in Chapter 3 (Garden Path and Thematic P600 conditions), and represent a disruption to successful processing as a result of the unlikely (ungrammatical) event.

4.3.2 Wh-dependencies

ERPs

The Wh-dependency elicits a broad positivity, from anterior to posterior channels, which is significant in early time windows and marginally significant in later time windows.

In the Ungrammatical+Wh-Dependency condition compared to the Ungrammatical condition there is neither a significant early negativity nor is there a significant posterior positivity.

TFRs

In the Wh-dependency condition, there are left anterior increases in Alpha band activity in early time windows, similar to the Long-distance dependency condition of Chapter 2, and the verb agreement violation conditions of both Chapter 2 and this experiment, however no additional increases in Theta or Beta activity, which might be expected given their presence in other long-distance dependencies (Chapter 2).

This increase in Alpha activity reflects the integration of the main verb with its filler argument, which begins as soon as the main verb is encountered (in-line with the *Active Filler Strategy* of Frazier, 1987).

It is unclear why there are not increases in Beta activity in this condition, which are seen in (ungrammatical) gaps in Chapters 2 and 3.

In the Ungrammatical+Wh-Dependency condition, in which the clausal main verb of a long-distance dependency has ungrammatical agreement morphology, frequency changes are also limited to increases compared to the Ungrammatical condition (similar to the Wh-dependency condition of this experiment, and the gaps of *wh*-dependencies in Chapter 2). In total, there are late increases in Theta, Alpha and Gamma activity, and increases in Beta activity in both early and late time windows.

4.3.3 Syntactic Reanalysis

ERPs

In the Garden Path condition, there is a significant broad posterior positivity, across early and late time windows, akin to the P600.

TFRs

In the Garden Path condition there are no significant event-related changes in frequency power.

Chapter 5

Conclusion

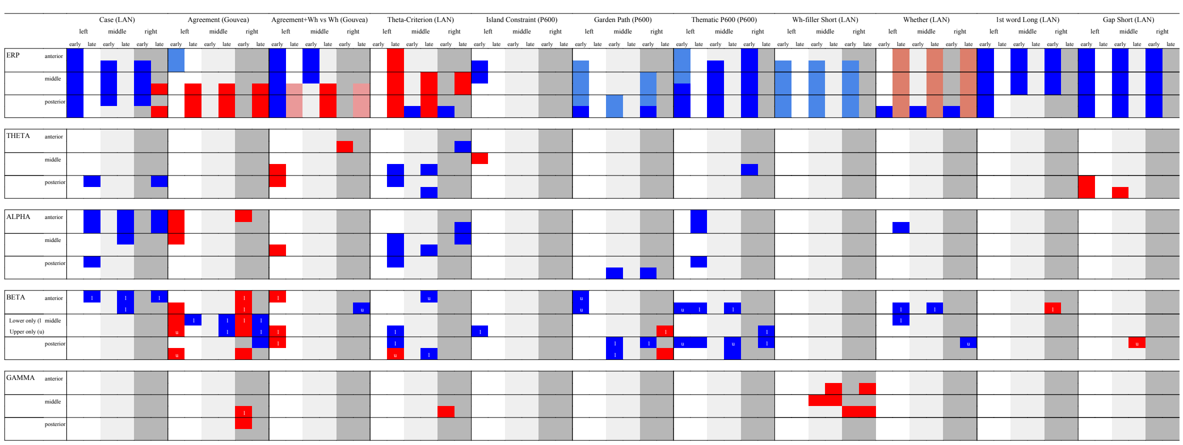
5.1 Are there multiple LANs?

One of the primary goals of this work was to determine whether the LANs commonly seen in response to grammatically distinct conditions (e.g., morphosyntactic violations, dependencies) represent similar underlying activity. Such a goal is critical to theories of sentence processing, which interpret qualitative differences/similarities in event-related activity as directly representative of syntactic processes.

LANs have been found following morphosyntactic errors (e.g., case, verb agreement and θ-Criterion violations like those seen in Chapters 2 and 4, as well as following island and phrase structure violations like those in Chapter 3). These early negativities have been interpreted as a reflection of the early, automatic processing of morphosyntactic information (Friederici, 2002), however LANs have also been found following fillers and gaps in long-distance *wh*-dependencies (often compared to short-distance dependencies; Kluender & Kutas, 1993a). These early decreases have been taken to represent the need for relatively greater working memory resources in the long-distance condition.

Here we begin by considering only those conditions in which a negativity is present in early time windows, which in this work includes in response to case violations, verb agreement violations (with and without *wh*-dependencies), θ-Criterion violations, island violations, Garden Paths, Thematic P600s, the *wh*-filler of the short-distance dependency condition, the complementizer *whether*, the first word of a long-distance dependency (immediately following the *wh*-filler), and the gap of the short-distance dependency (again, immediately following the *wh*-filler). The early negativities associated with these conditions appear in primarily left (anterior) areas, though in many cases are more widespread, and in some cases are more posterior (all such variations have been documented in the literature).

Figure 5.1: Conditions which elicit a LAN (all experiments)



Taken together, there are mixed results across all frequency bands, which is an initial indication that *no single pattern of frequency activity explains all cases of the LAN.*

THETA

Considering the Theta band for a moment, the mixed results of this work are particularly interesting, given the hypothesis that the LAN is representative of increases in working memory (e.g., Gibson, 2000, see Chapter 1.1 for discussion). Theta band activity has been associated with increased demands in working memory (Hald et al., 2006; Weiss et al., 2005), and has been linked in particular to the construction of a working memory representation of a sentence (increases in power and coherence, respectively; Bastiaansen et al., 2002; Weiss & Mueller, 2003), as well as the retrieval of lexical semantic information (Pulvermüller, 1999, 2001; Bastiaansen et al., 2008). If the LAN is simply a reflection of increased demands on WM resources, we might expect to see increases in Theta activity in all cases of early negativities. Rather, increases in Theta band activity were limited to the Verb Agreement Violation condition in which the violation occurs on the main verb of a *wh*-dependency, the Island Violation condition, and the gap of the short-distance dependency. Interestingly, all of these cases represent a point of dependency resolution following a *wh*-filler, which seems to confirm the notion that *Theta activity is associated with the retrieval of lexical-semantic information*, and in particular *retrieval associated with construction and resolution of a dependency.*

BETA

Despite the fact that no single pattern of frequency activity occurs in all cases in which there is an early negativity, there are variations in Beta activity (increases or decreases) across nearly all of the LAN conditions. The only condition in which there was an early negativity with no variation in Beta activity was also the only condition in which the early negativity was only marginally significant (the *wh*-filler of the short-distance dependency). All of the 10 other conditions had significant variations in Beta activity, which indicates that *the process(es) Beta activity indexes are related to those which elicit a LAN.*

Eight of these 10 conditions were found to have *decreases* in Beta activity, in primarily late time windows. The conditions eliciting decreases were all violations (with the exception of the *wh*-complementizer *whether*), and (notably) no such decreases were found in conditions associated with the processing of a dependency (*wh*-filler, or the word immediately following it in both the short- and long-distance dependency). Finally, these decreases were nearly always in the late window (500-900ms) more classically associated with the P600, however in those few cases in which there was a more global disruption to the processing of syntactic (thematic) information, decreases appeared in early time windows (Island Violations, Garden Paths, Thematic P600s). In sum, *decreases in Beta activity represent violations of morphosyntactic expectation, with variability in the latency of the response based on the level of disruption to processing.*

Increases in Beta activity were also apparent, in early and late time windows, among a more narrow set of conditions. These cases span across violation and dependency conditions, including Verb Agreement Violation conditions, θ-Criterion violations (a gap without a *wh*-filler), Garden Path sentences, and the word immediately following the *wh*-filler in both the short- and long-distance dependency.

Altogether, *increases in Beta activity appear related to the processing of the complex syntactic representations* – including both the creation, manipulation and maintenance of those representations during online processing (Bastiaansen et al., 2010; Shahin et al., 2009). Anomalies during this processing, particularly on critical items like a verb, may cause the need for additional activation of representations in an attempt to overcome the anomaly and integrate the verb into the current representation. This may lead to a state in which several (more complex) representations are being activated and maintained during online processing – a state which is perhaps similar to that which occurs following the first word of a long-distance dependency. In this latter case, there is the addition of another argument (e.g., subject of the embedded clause) prior to resolution of the argument represented by the *wh*-filler with the main verb. This would explain why there is no corresponding Beta increase/LAN following the first word of a *whether* clause, as *whether* does not represent a verbal argument.

5.1.1 Summary

Altogether, these results find an array of responses in the time window of the LAN, and no pattern of changes in frequency band activity that perfectly co-occur with the LAN. It therefore appears as though multiple sentence processing mechanisms are concurrent with the LAN, and are indexable with changes in frequency activity, but that *changes in frequency power alone cannot tell us whether there is more than one LAN.*

While changes in frequency synchrony power do not appear to represent the identical information captured by the LAN, the addition of this information offers a more rich interpretation of the events occurring in early time windows. For example, in the Island Violation condition of Chapter 3, the frequency response in early time windows can be interpreted as both the attempt to resolve an apparent gap (increased Theta band activity), *and* the detection of a (major) anomaly, which in this case is the boundary of an adjunct island. These processes are plausible from a processing perspective, and it is therefore desirable that these events be represented in our measures of processing.

5.2 The functional significance of the LAN

Overall, it appears as though the LAN *co-occurs* with, but is not solely representative of working memory processes involved in the retrieval of lexical information for dependency resolution – reflected in increases in Theta band activity. Theta band increases occur in grammatical and ungrammatical dependencies, beginning within several hundred milliseconds of the main verb of the dependency/from the onset of the dependency gap. This activity does not demonstrate sensitivity to the length of the dependency, and in fact seems to reflect top-down *expectations* of a gap. This explains why there is no such increase in the θ-Criterion Violation condition, where no *wh*-filler is present, only a(n unexpected) gap.

While there is co-occurence of the LAN and such working memory processes, this activity (increases in Theta band activity representing active parsing of dependencies) does not appear to represent the functional significance of the LAN, given its absence in all cases in which no dependency is posited. *Such evidence undermines proposals that the LAN represents a common set of working memory resources utilized during dependency and morphosyntactic processing* (Vos et al., 2001), which would predict increases in Theta activity in all cases of the LAN.

Conditions which elicit a LAN also coincide with the processing of complex syntactic representations reflected in increases in Beta activity in many conditions (though these increases do not always appear in early time windows). As processing of a sentence progresses, incoming arguments are integrated into the sentence's growing representation, which is reflected in continuous increases in Beta activity (Bastiaansen et al., 2010). In the cases where multiple representations are being manipulated simultaneously, Beta activity increases above baseline, particularly in cases where multiple arguments are encountered prior to resolution with the clausal main verb. This includes examples where an embedded clause subject is encountered after a *wh*-filler (e.g., *The cameraman knew <u>who</u> <u>the</u> former mayor would honor before the fireworks*), and when a DP is encountered (embedded within a larger PP) following an omitted (obligatory) verbal argument (θ-Criterion Violation, **The cameraman knew that the former mayor would honor before <u>the</u> fireworks*). This level of processing is also achieved in cases where processing of the clausal main verb occurs under anomalous conditions (e.g., *number* agreement errors, **The cameraman knew that the former mayor would <u>honors</u> before the fireworks*; verbs in garden path sentences, *The woman heard that the broker persuaded to* conceal *the transaction was sent to jail*). Such conditions may engender additional activation and manipulation of argument representations, in an attempt to continue with successful processing.

Finally, conditions which elicit a LAN also coincide with the detection of unexpected morphosyntactic information, represented by decreases in primarily later time windows. These results point to a process of evaluation of processing which is sensitive to the probability of (syntactic) events. Such sensitivity has been demonstrated in the early version of the LAN (the ELAN) by Lau et al. (2006), and is well-known for the P600 (Coulson et al., 1998; Kim & Chung, 2008; Engel & Fries, 2010; Jenkinson & Brown, 2011). Taken together, *this points to the (E)LAN and the P600 representing 'two sides of the same coin' in this evaluative process.*

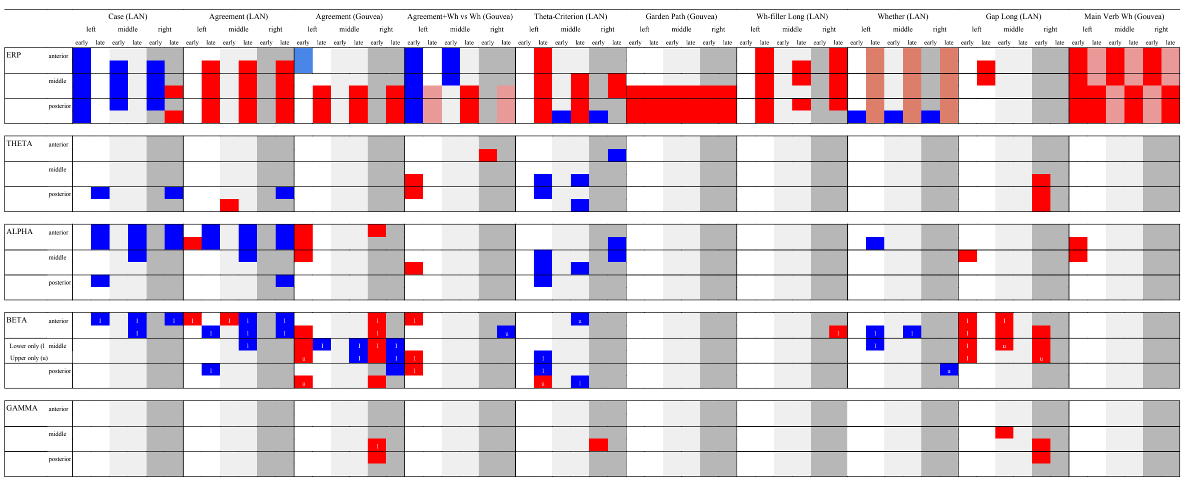
5.3 Are there multiple P600s?

P600s have been found in a wide array of conditions, including following syntactic ungrammaticalities (Neville et al., 1991; Hagoort et al., 1993; Osterhout & Holcomb, 1992; Hagoort et al., 1993; Osterhout et al., 1994; Coulson et al., 1998; Friederici et al., 1993; Osterhout & Mobley, 1995; Osterhout, 1997), aspects of *wh*-dependency processing (e.g. Kaan et al., 2000; Fiebach et al., 2002; Felser et al., 2003; Phillips et al., 2005), and cases of reanalysis (not ungrammaticalities, e.g. Friederici et al., 1996; Osterhout & Holcomb, 1992; Osterhout et al., 1994).

In keeping with the goal of determining whether a single ERP like the P600 is the result of a common or varied sets of processes, instances of P600-inducing conditions have been re-examined from an alternative analysis perspective. Here we consider only those conditions in which a late positivity is present.

In this work a broad, posterior positive deflections are found following verb agreement violations, θ-Criterion violations, (some instances of) the *wh*-filler *who*, the *wh*- complementizer *whether*, (some instances of) gaps in long-distance dependencies (anterior positivity), main verbs of *wh*-clauses, and (some instances of) garden path sentences.

Figure 5.2: Conditions which elicit a P600 (all experiments)



ALPHA AND BETA

Taken together, these results find late-window decreases in (Alpha and) Beta activity following violations (similar to Davidson & Indefrey, 2007) like case, verb agreement and θ-Criterion violations[1] [2]. This common set of responses may be understood as indicating an increase in attentional state (Alpha decrease) in response to an unexpected syntactic event (Beta decreases). Here again (similar to responses found in LAN-eliciting conditions), *late positivities in response to violations or unexpected syntactic events appear to index an evaluative process which is sensitive to the probability of a (syntactic) event.*

[1]Alpha and Beta decreases are also found following the *wh*-complementizer *whether*, which does not represent a syntactic error, but may represent an unexpected event at that position given that it only appeared 1/8 of the time.

[2]These decreases are *not* found following the Garden Path condition, which has *no* significant change in frequency activity *overall*, and may represent an instance of Type II error

5.3.1 Summary

Altogether, these results find an array of frequency power decreases in (primarily) Alpha and Beta activity which co-occur with a specific subset of P600 conditions. These decreases are limited to cases of unexpected syntactic events (including, but not limited to ungrammaticalities). Positivities in response to fillers and gaps are (notably) *not* correlated with decreases in frequency power in late windows (only increases in activity, often in early windows described in 5.1 above). *These results point to a distinction in the nature of the P600 response to dependency-related vs. anomalous items.* These results also support the notion that the P600 response is sensitive to the probability of items (rather their status as grammatical or ungrammatical Coulson et al., 1998; Lau et al., 2006; Kim & Chung, 2008; Engel & Fries, 2010; Jenkinson & Brown, 2011).

In conclusion, *this work points to the existence of multiple P600s*, at least one of which is represented by decreases in (Alpha and) Beta activity. There is a strong distinction in frequency activity underlying P600s elicited during the processing of dependencies compared to P600-conditions in which there is a violation-of-expectation. Such a distinction has been observed in results dating back to the original works which discovered the P600, which have often found more anterior (and, at times earlier latency) versions of the P600 in response to dependencies and garden paths (Osterhout & Holcomb, 1992; Hagoort et al., 1999; Friederici et al., 2002; Kaan & Swaab, 2003; Gouvea et al., 2009). In comparison, the P600 elicited following violations are often more posterior, and are in the majority of cases preceded by an anterior negativity.

5.4 The functional significance of the P600

This work points to the idea that *one P600 reflects an evaluative process which is sensitive to the probability of events, both grammatical and ungrammatical.* This response is reflected in decreases in (Alpha and) Beta activity in late time windows, which appear (fairly uniformly) across an array of morphosyntactic violations, garden path and Thematic P600 sentences. There is no indication in these results of a difference in conditions of reanalysis compared to violations, nor is there evidence of a difference in the nature of the response to Thematic P600 sentences (which have been argued by some to reflect a mismatch of individual processing streams). In fact, the breadth of the decreases associated with P600s in this work extends across frequency bands which have been associated with individual processing streams (Alpha: semantic, Beta: syntactic). If, as some have argued, the P600 reflected a mismatch in the validity of semantic (anomalous) and syntactic (grammatical) streams, one might expect divergence in frequency activity to reflect this. However, these results indicate a far more uniform modulation of frequency activity in 'violation (of expectation) P600s', which as a result appears to *reflect a more general monitoring mechanism*.

Results from this work are consistent with the notion that *one P600 reflects processes of complex syntactic integration*, for example those involved in the construction of long-distance dependencies. These 'construction P600s' often appear in more fronto-temporal channels compared with the more posterior P600 of violations (of expectation) (Friederici et al., 2002; Kaan & Swaab, 2003; Gouvea et al., 2009), and in this work are more likely associated with *increases* in activity. The frequency response to this condition set is more varied than in the case of the 'violation P600,' and additional investigation of the source of this P600 is warranted.

5.5 Are ERPs and the oscillatory activity observed here one in the same?

While oscillatory activity has been demonstrated to represent communications in neural networks both local and global, one may ask whether it is necessarily the case that the oscillations occurring at the same time as an event-related potential (ERP) are mutually inclusive of the information represented in that ERP. In other words, could it be the case that there are changes in the relative strength of various frequency bands in response to a stimulus, which are *independent* of the ERPs that co-occur with those changes? Or, put yet another way, must it be the case that changes in frequency activity *explains* the occurrence of ERPs, or could they in fact be separate entities which also occur in response to certain grammatical conditions and violations?

Work to both points has been presented in the literature, and as of this writing there is no single consensus on this issue. For many years, *additive* or *amplitude-modulation* models of event-related potentials have advocated for the evoked nature of ERPs, in which additional time-locked, phase-locked activity is generated in response to a stimulus, and is combined with the ongoing oscillations in the EEG. This activity is uncovered by the grand-averaging procedure, and is what we know as the ERP (Mäkinen et al., 2005; Mazaheri & Jensen, 2006; Mazaheri & Picton, 2005; Shah et al., 2004).

There is evidence for the additive model in work by Shah et al. (2004), in which visual-evoked ERPs were found among little background activity in intracortical animal recordings.

On the other side of this debate is the perspective that ERPs are generated by modulations of ongoing oscillatory activity, which occur in response to a stimulus. It has been assumed for many years that stimulation induces a partial phase-resetting of the ongoing EEG (Başar et al., 1980; Brandt et al., 1991; Makeig et al., 2002; Sayers et al., 1974b), and in 2004 work by Makeig et al. showed that at least some ERPs are the result of induced *phase-resetting* of ongoing oscillatory activity (and thus the ERP is comprised of existing oscillatory activity). Work since this time has furthered the *phase-reset* perspective of ERPs, in particular the role of the phase-reset of alpha band activity in the generation of the event-related potential (Hanslmayr et al., 2007).

Attempts have been made to quantify the amount of phase-resetting, or the 'phase-locking' factor (PLF Makeig et al., 2004; Herrmann et al., 2005; Tallon-Baudry & Bertrand, 1999b) that occurs across trials, however it has been pointed out that the amount of phase-locking could also be a result of the convolution of additive activity with the ongoing EEG.

While the debate about the source of ERPs in the EEG is still under debate, one approach that can be taken in work of this nature is to compare the spectrum of the evoked activity to the spectrum of the induced activity, similar to the comparison shown in (Tallon-Baudry & Bertrand, 1999b). The evoked activity spectrum can be obtained by performing time-frequency (TF) analysis on the grand average activity, or ERP. The induced activity, on the other hand, which is measured in this work computes the averages of time-frequency representations of individual trials. By comparing the results of these analyses, one can identify the frequency activity within the ERP to that which is captured in individual trials. If the frequency components of the ERP are the same as those seen to change in individual trials, then there is additional evidence that these fluctuations in frequency activity are representative of the same processing measured in the ERP.

5.6 Summary and Future Directions

The goal of this work was to complete an exploratory analysis of canonical ERP-inducing linguistic conditions, from an alternate analysis perspective. That is, to examine the brain's response to certain linguistic conditions in terms of the frequency activity generated - conditions which are grammatically distinct but yet which are typically followed by a small number of amplitude-domain responses. Overall, this work sought to uncover patterns in the brain's frequency response to grammatically distinct conditions, to see whether that activity might distinguish such conditions from one another where amplitude activity does not. Furthermore, this work aimed to better characterize the processes at hand during various grammatical and ungrammatical sentence processing contexts, which may be represented by patterns of frequency activity *as well as* amplitude activity.

In the end, this work has produced a new typology of responses, including several distinctions in frequency band activity that fall along grammatical lines. To begin, decreases in Beta band activity in (primarily) late time windows occur in response to low-probability events (e.g., violations, unexpected syntactic structure), and are absent in cases of items involved in *wh*-dependencies (e.g., *wh-filler*). These decreases occur in later time windows (400-900ms) for more local violations of morphosyntactic expectation such as Case, Agreement and θ-Criterion violations; however in cases of more global disruptions in syntactic (thematic) processing such as those found following Island Violations, Garden Path sentences and the Thematic P600, these decreases occur much earlier (200-500ms). These results are evidence that at least a subcomponent of the larger sentence processing architecture is sensitive to the detection of low-probability events (from the perspective of the parser), and is agnostic to the processing associated with the creation and resolution of dependencies. Both an early version of the LAN (ELAN) and the P600 have previously been associated with the detection of low-probability events, with results indicating a direct relationship between the ERP amplitude and the probability of an event (Coulson et al., 1998; Lau et al., 2006; Kim & Chung, 2008; Engel & Fries, 2010; Jenkinson & Brown, 2011). It may be the case that the (E)LAN and P600 *in combination* represent this processing, as an early and a late component of a more general mechanism which is sensitive to probabilities of (syntactic) events. This would explain the high correlation of the two ERPs, and the presence/absence of the early component in some cases may reflect the level of transparency of the grammatical violation, as well as perhaps the level of impact of that violation on the overall system's processing. If this is correct, *one should be able to parametrically vary the strength of the (E)LAN and P600 in conditions of unexpected syntactic constructions (orthogonal to grammaticality)*, and the strength of the components should be consistently related across conditions (e.g., high correlation of peak amplitudes in a trial-by-trial analysis). Finally, with these results this work has provided additional evidence for *the existence of more than one P600*, with one late positivity reflecting evaluations of probabilities during processing, and the other reflective of aspects of processing of complex syntactic structures such as dependencies.

This work has also uncovered a number of early *increases* in Beta activity in response to a variety of syntactic events, including agreement errors, gaps and *wh*-fillers. These responses occur *across* violations and dependencies, providing evidence that at least certain subprocesses in the sentence processing architecture treat violations and dependency-related elements as similar. Taken together, this group of conditions appears to represent cases in which there are morphosyntactic cues from the environment that non-canonical syntactic processing is occurring. Beta activity has previously been shown to be responsive to overt environmental cues (Jenkinson & Brown, 2011; Engel & Fries, 2010; Kim & Chung, 2008), and has also been tied to the manipulation of (syntactic) representations (Bastiaansen et al., 2010; Shahin et al., 2009) – a type of processing which may be further engaged during non-canonical syntactic processing. Overall, this is additional evidence of the *role of Beta activity in the construction of syntactic representations*, and predicts that *increases in Beta band activity should occur throughout grammatical syntactic processing, with additional increases in more complex processing environments.*

In addition to the role of Beta activity in syntactic processing, this work also identifies *the role of Theta band activity in the processing of wh-dependencies*, namely in the retrieval processes associated with the resolution of a gap. Theta increases are found in response to gaps only in cases in which a *wh*-filler preceded them, implicating Theta in either (i) anticipatory gap-resolution following the trigger of a filler, or (ii) the successful resolution of a gap with its filler (when the properties of the filler are actually accessed). This activity is primarily within the early time windows of the LAN, and co-occurs with increases in Beta activity in all but one case (the Island Violation condition). *This predicts that such increases should appear in cases where a dependency, or perhaps any relation requiring the retrieval of lexical-semantic information*, and it remains to be seen whether these increases reflect the successful retrieval of the necessary feature information, or simply that such retrieval was predicted

Finally, *early increases in left fronto-temporal Alpha band activity reflect disruptions in the processing of verbal information.* These increases span across violations *and* dependency conditions, appearing in response to main verbs expressing agreement errors (Chapter 2 and 4), as well as verbs and gaps in dependencies (Chapter 2 and 4). This result is consistent with work by Tyler et al. (2004), in which LIFG was shown to be more responsive to the processing of complex verbal information compared with the processing of complex nouns. Taken together, it appears that *verbal information processing may engage particular processing mechanisms not previously identified by event-related potentials*, which utilize alpha frequency (8-12Hz) activity in areas akin to LIFG. This activity is less straightforwardly connected to the LAN and P600 in either its eliciting conditions or its latency, and may represent activity not directly indexed by these ERPs. Rather, in this case *oscillatory activity may be indexing processes ERPs are not sensitive to* - and contributing novel information about the sentence processing architecture.

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Appendix A

Appendix

A.0.1 Reanalysis with subset of subjects (15): ERPs and TFRs

Given that the canonical event-related responses to the experimental stimuli were not found in all cases, a second analysis was run in which subjects' individual ERPs were examined, and a subset of subjects were selected. In this case, the result was a down-selected group of 15 subjects, whose EEG response to these well-vetted experimental conditions appeared typical (i.e., had the canonical N1/P2 complex, lacked noise in the signal). By analyzing this group we can distinguish whether a lack of expected ERP response in the larger group is a result of noise in the data of certain subjects, or a more broad data quality issue. Down-selecting the subject data reduces power in the analysis, however the size of this group (15 subjects) is within the lower bounds of the typical group size in which ERPs like the P600 are apparent.

Reanalysis with subset of subjects (15): Case Violation

ERPs

CC The cameraman knew that the former mayor would honor *them* before the fireworks.
CV The cameraman knew that the former mayor would honor *they* before the fireworks.

Figure A.1: Reanalysis with subset of subjects (15), Case Violation: ERPs

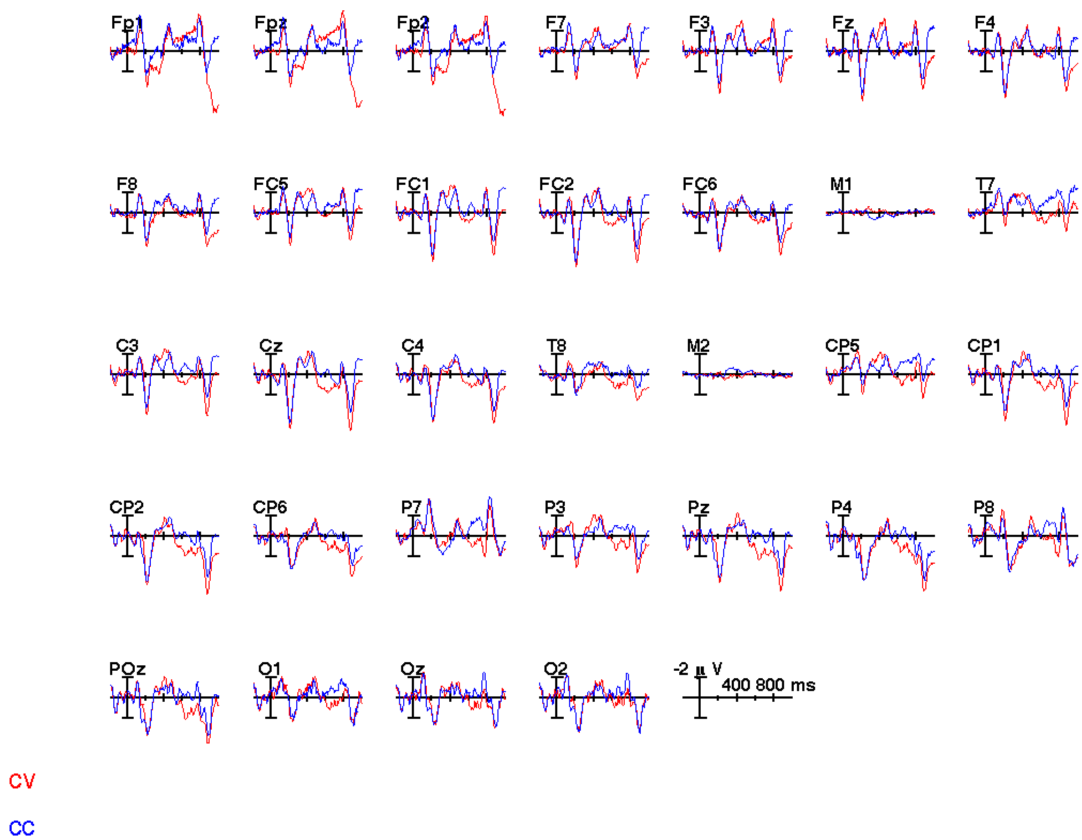
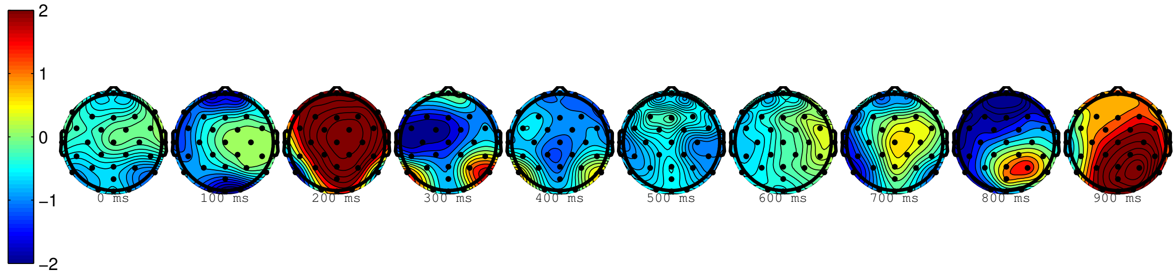
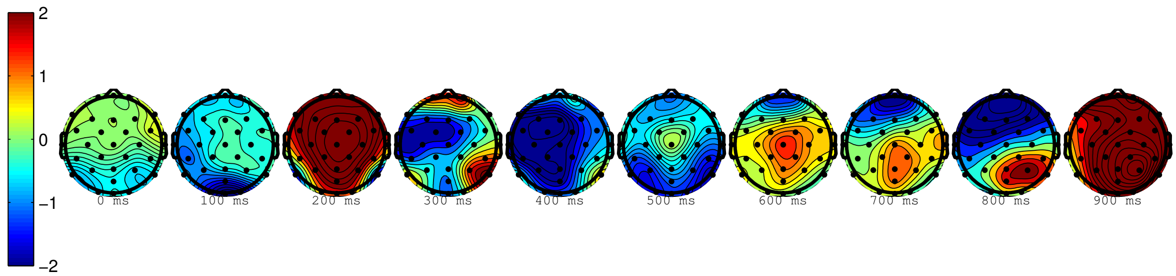


Figure A.2: Reanalysis with subset of subjects (15), Case Violation: topoplots

Case Control



Case Violation



Difference plots

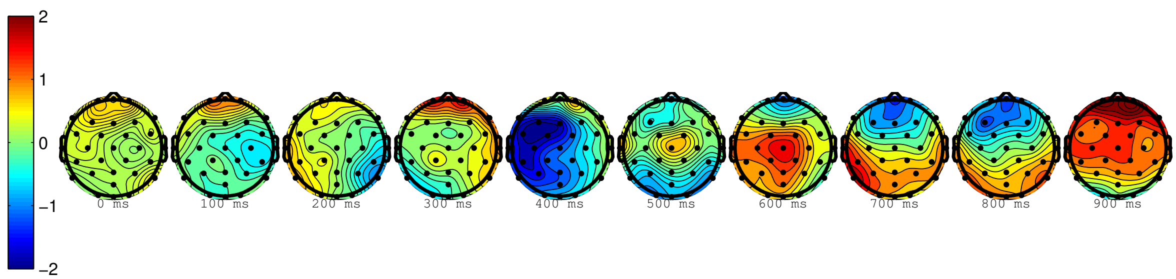


Figure A.3: Reanalysis with subset of subjects (15), Case Violation: t_{max} permutation tests

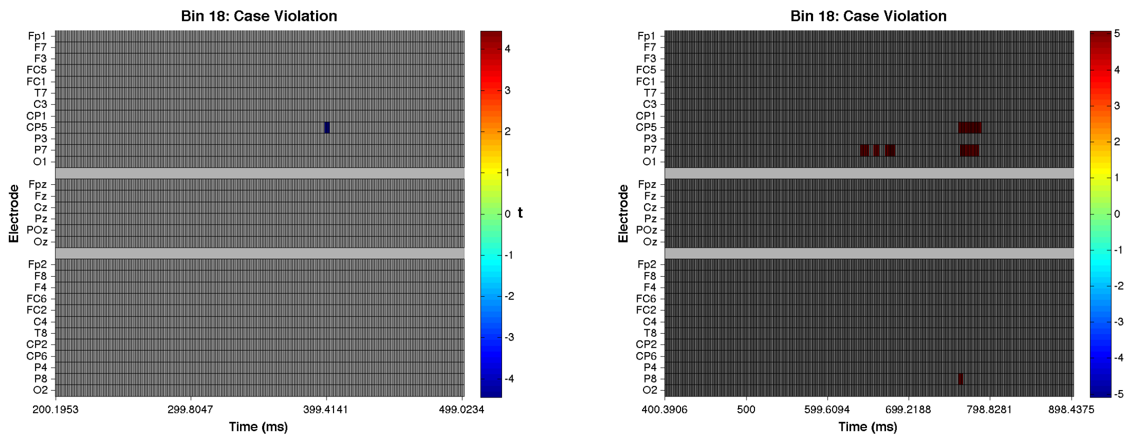
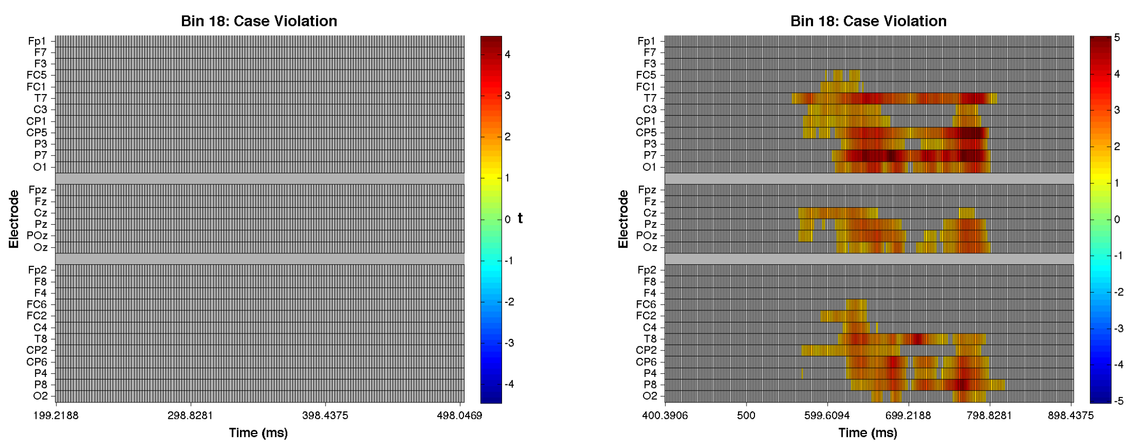


Figure A.4: Reanalysis with subset of subjects (15), Case Violation: cluster mass permutation tests



TFRs

Figure A.5: Reanalysis with subset of subjects (15), Case Violation: TFR

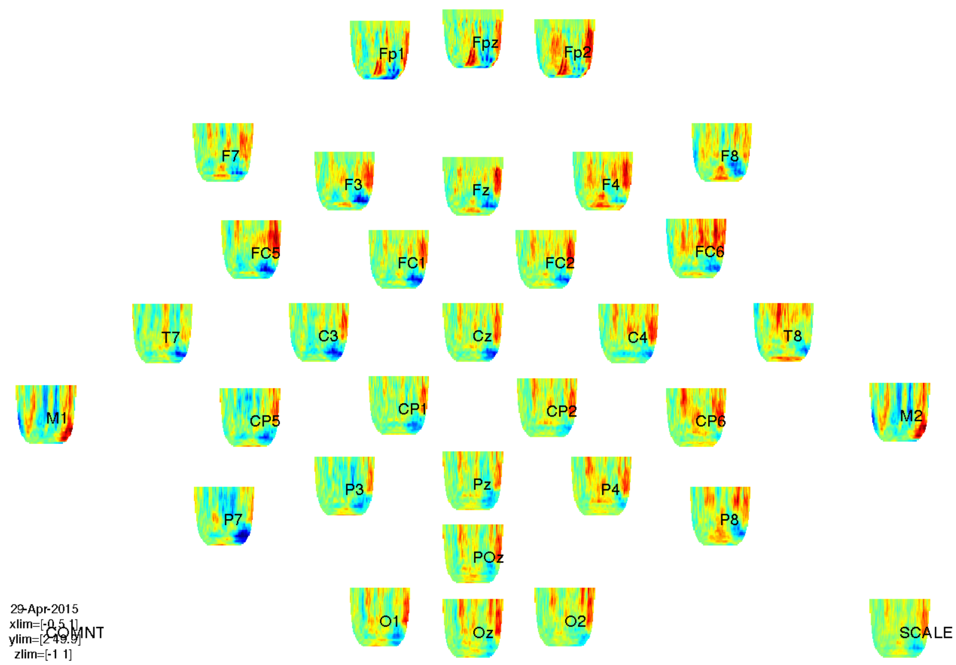


Figure A.6: Reanalysis with subset of subjects (15), Case Violation: Theta band (4-7Hz) masked stats TFR

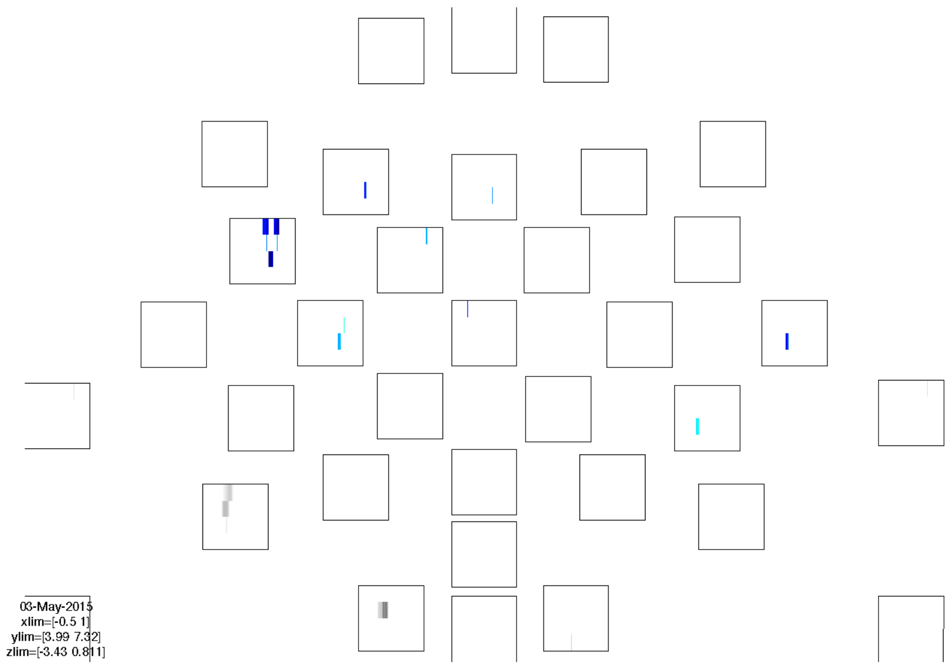


Figure A.7: Case Violation Condition: Theta band (4-7Hz) masked stats TFR, significant channels

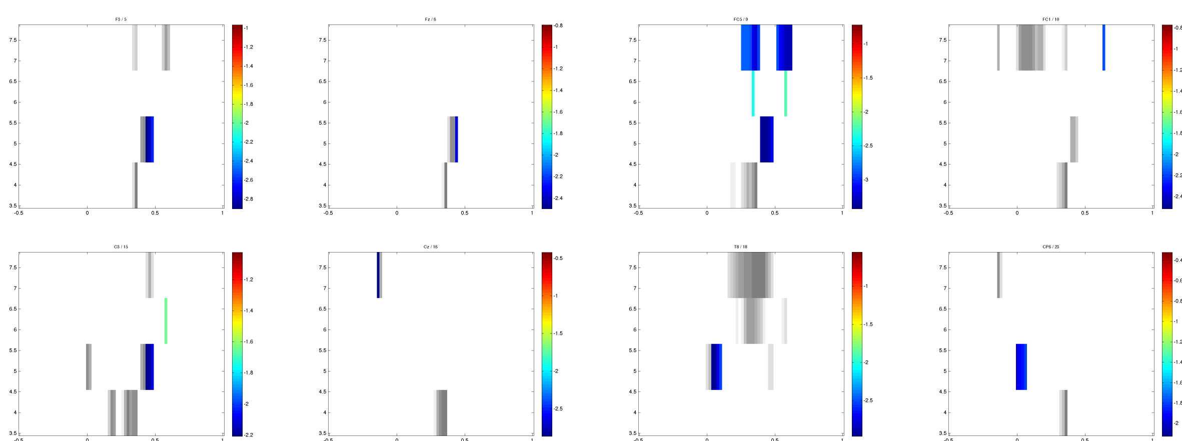


Figure A.8: Reanalysis with subset of subjects (15), Case Violation: Alpha band (8-12Hz) masked stats TFR

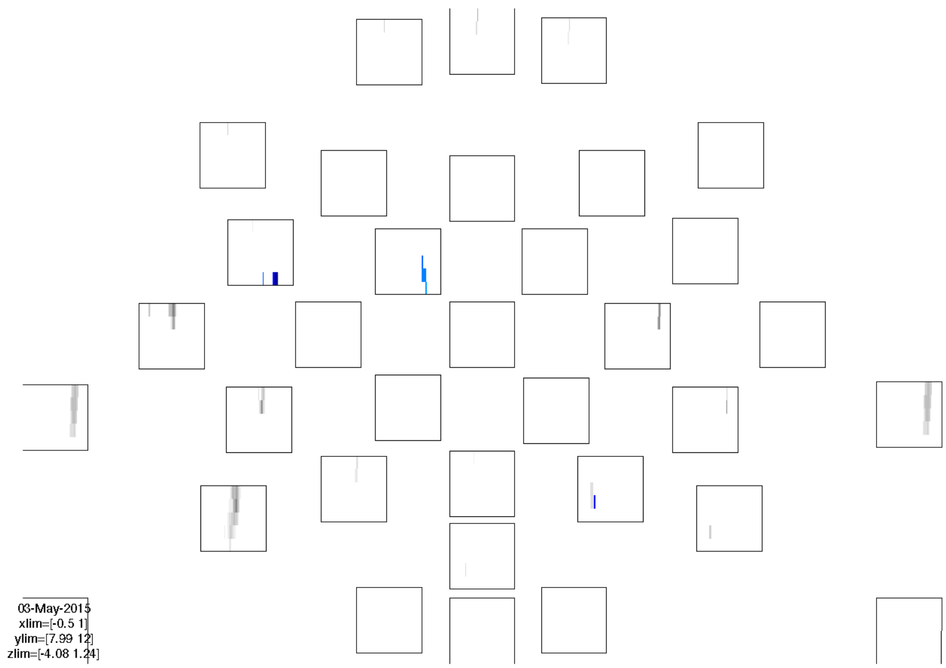


Figure A.9: Case Violation Condition: Alpha band (8-12Hz) masked stats TFR, significant channels

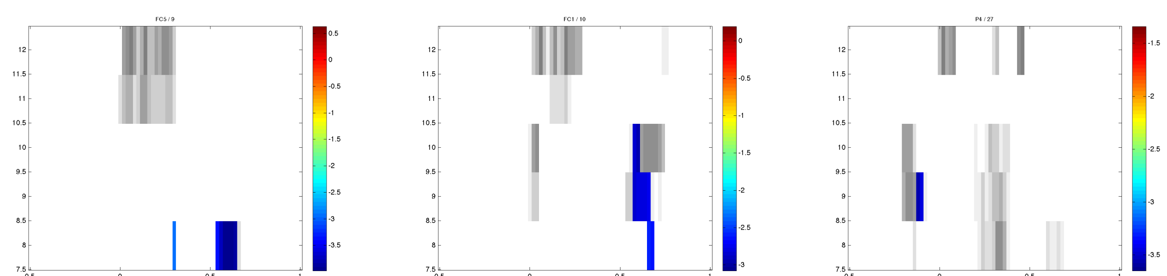
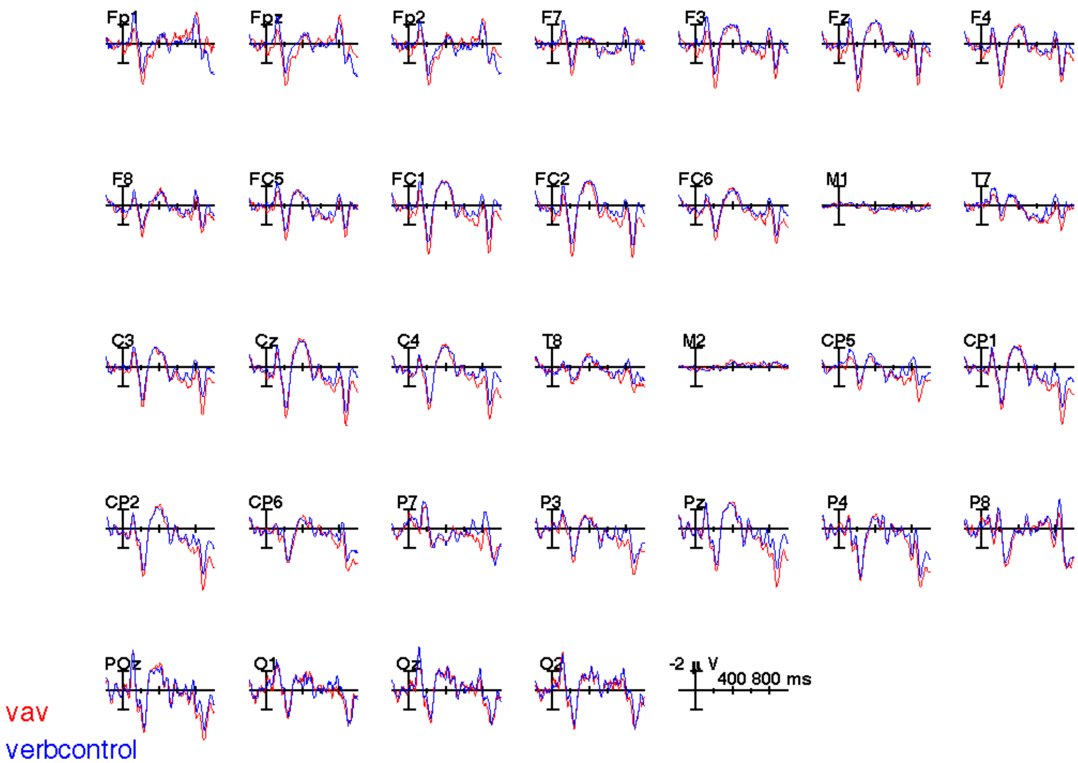


Figure A.10: Reanalysis with subset of subjects (15), Verb Agreement Violation: ERPs



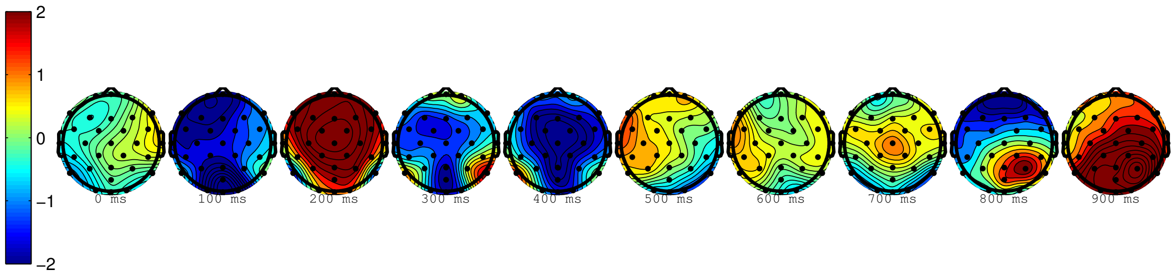
Reanalysis with subset of subjects (15): Verb Agreement Violation Condition

CONTROL	The cameraman knew *that* *the* former mayor would *honor* *the* soldiers before the fireworks.
VAV	The cameraman knew that the former mayor would *honors* the soldiers before the fireworks.

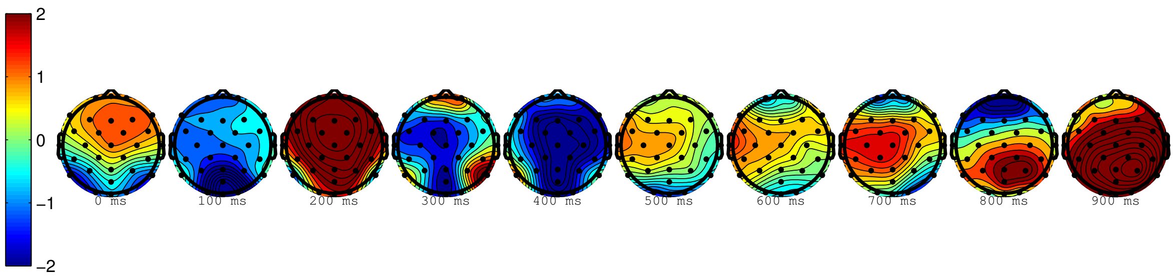
ERPs

Figure A.11: Reanalysis with subset of subjects (15), Verb Agreement Violation: topoplots

Verb Control



Verb Agreement Violation



Difference plots

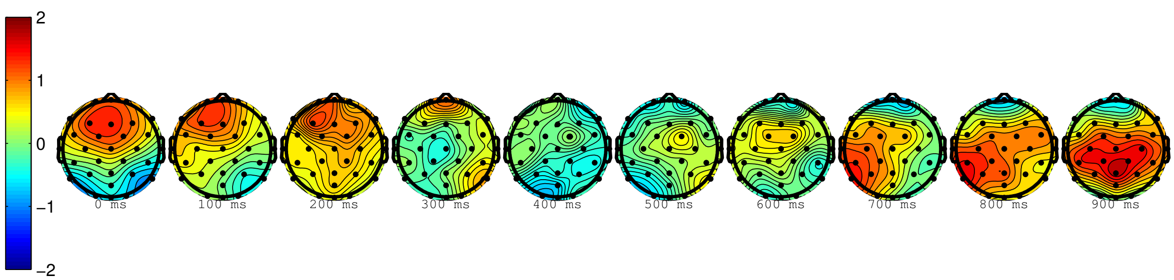


Figure A.12: Reanalysis with subset of subjects (15), Verb Agreement Violation: t_{max} permutation tests

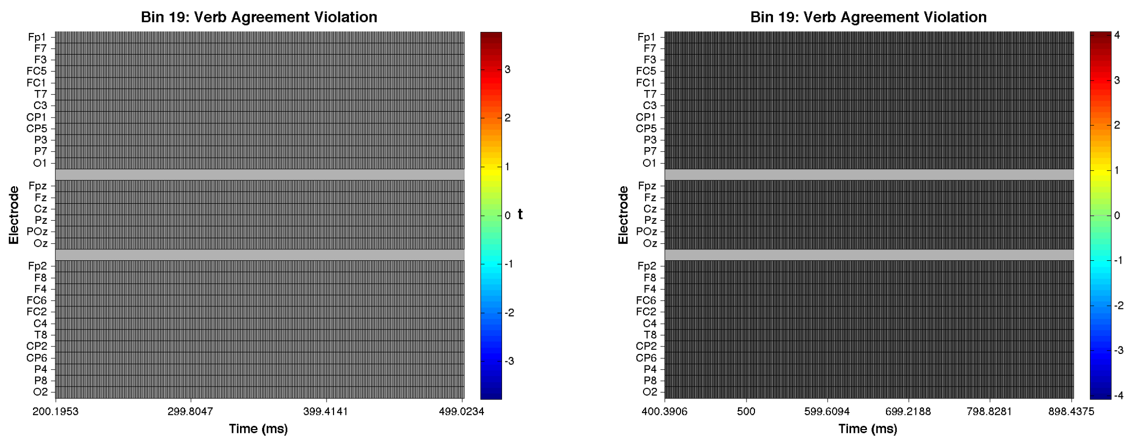


Figure A.13: Reanalysis with subset of subjects (15), Verb Agreement Violation: cluster mass permutation tests

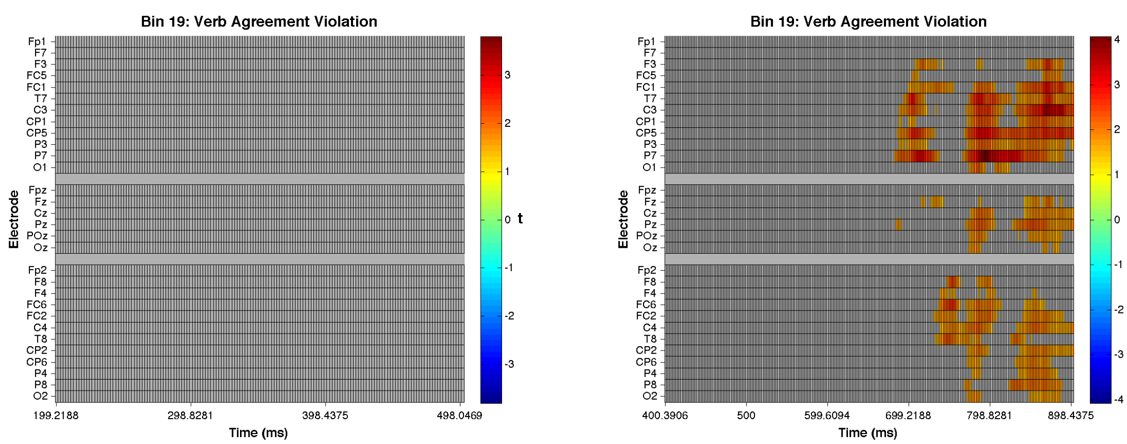
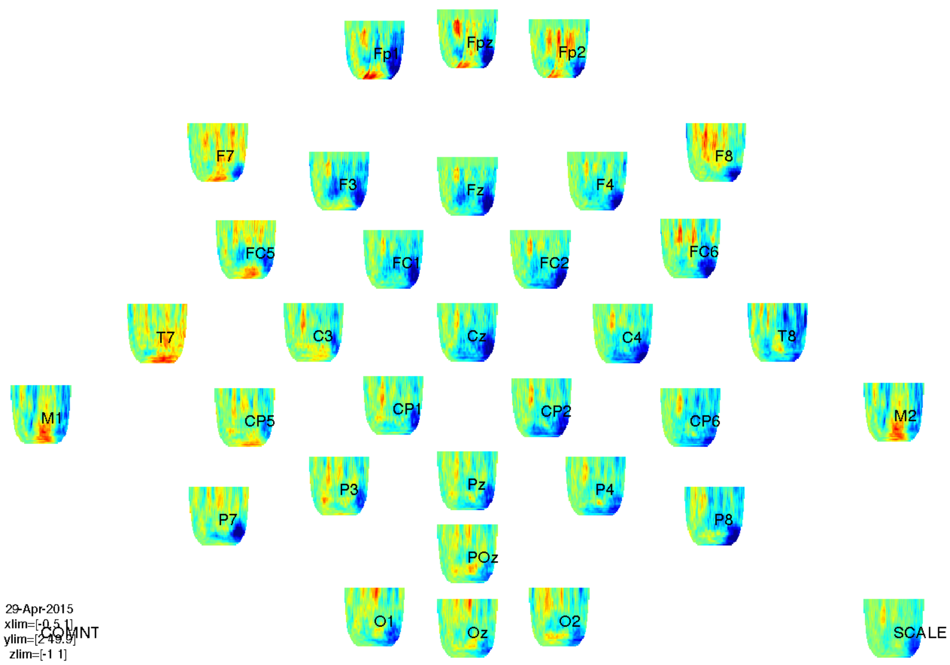


Figure A.14: Reanalysis with subset of subjects (15), Verb Agreement Violation: TFR



TFRs

Figure A.15: Reanalysis with subset of subjects (15), Verb Agreement Violation: Alpha band (8-12Hz) masked stats TFR

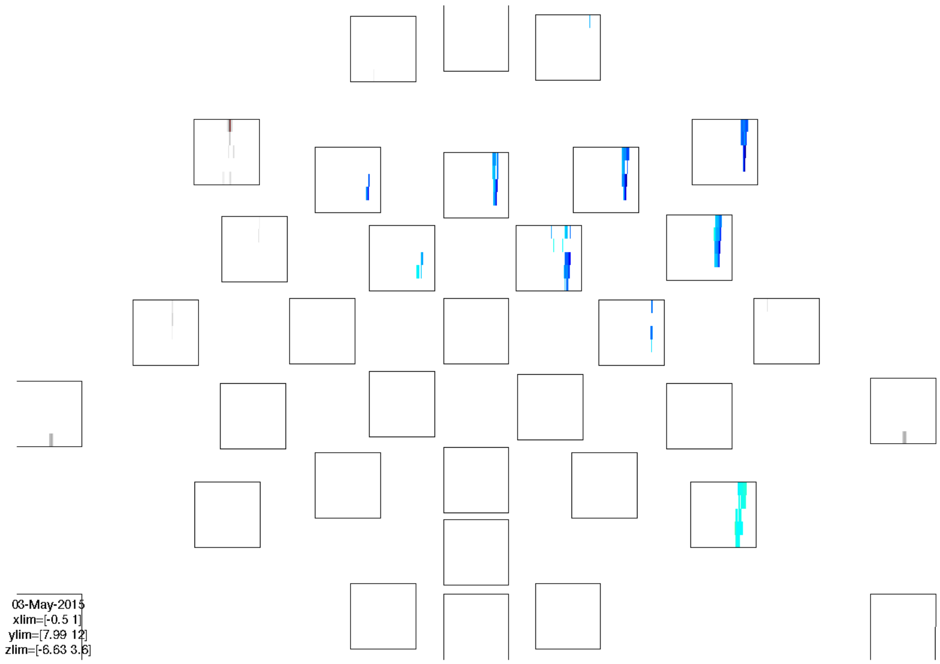


Figure A.16: Reanalysis with subset of subjects (15), Verb Agreement: Alpha band (8-12Hz) masked stats TFR, significant channels

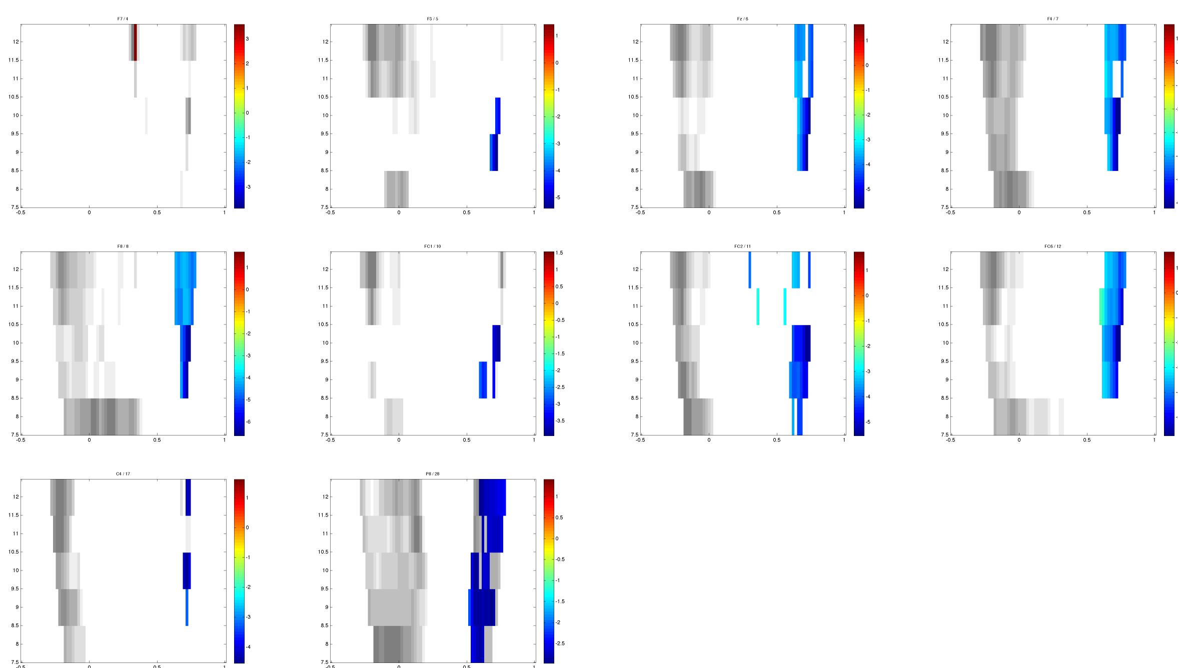


Figure A.17: Reanalysis with subset of subjects (15), Verb Agreement Violation: Lower Beta band (13-20Hz) masked stats TFR

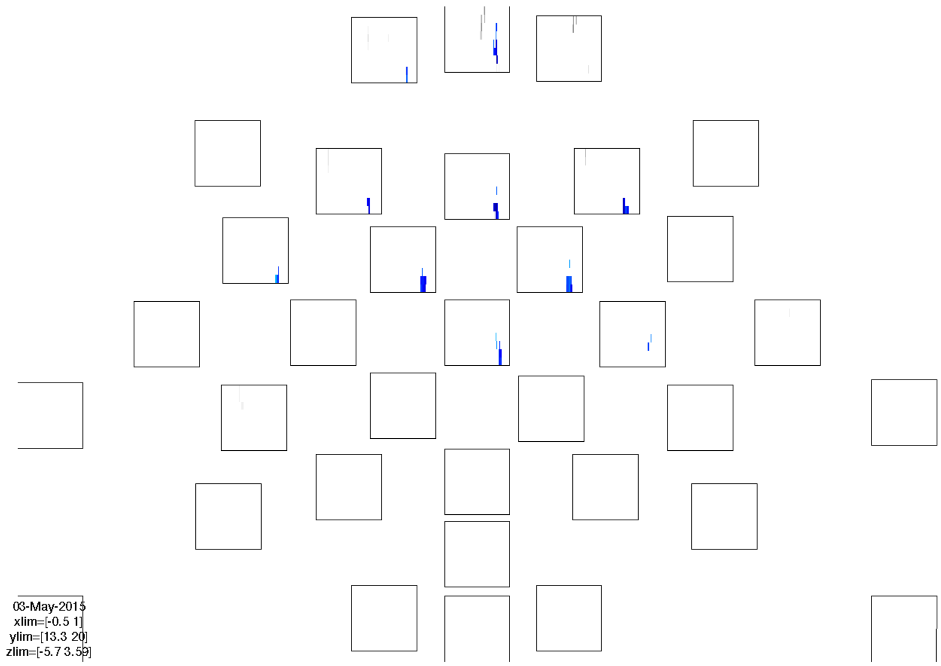


Figure A.18: Reanalysis with subset of subjects (15), Verb Agreement Violation: Lower Beta band (13-20Hz) masked stats TFR, significant channels

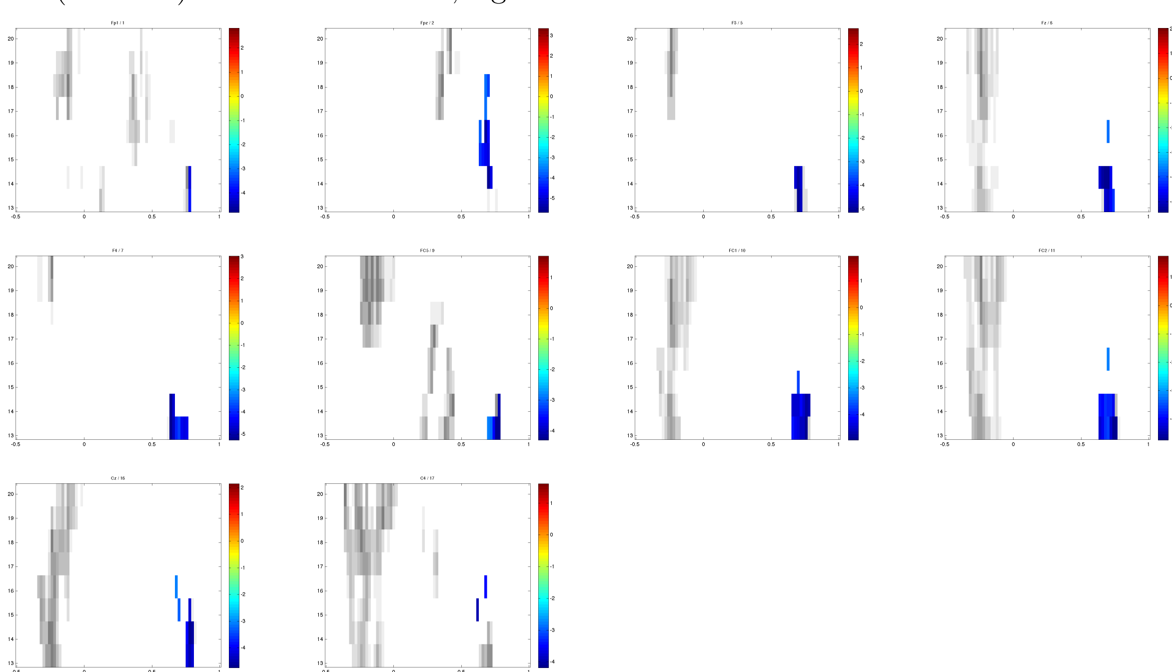


Figure A.19: Reanalysis with subset of subjects (15), Verb Agreement Violation: Gamma band (31-40Hz) masked stats TFR

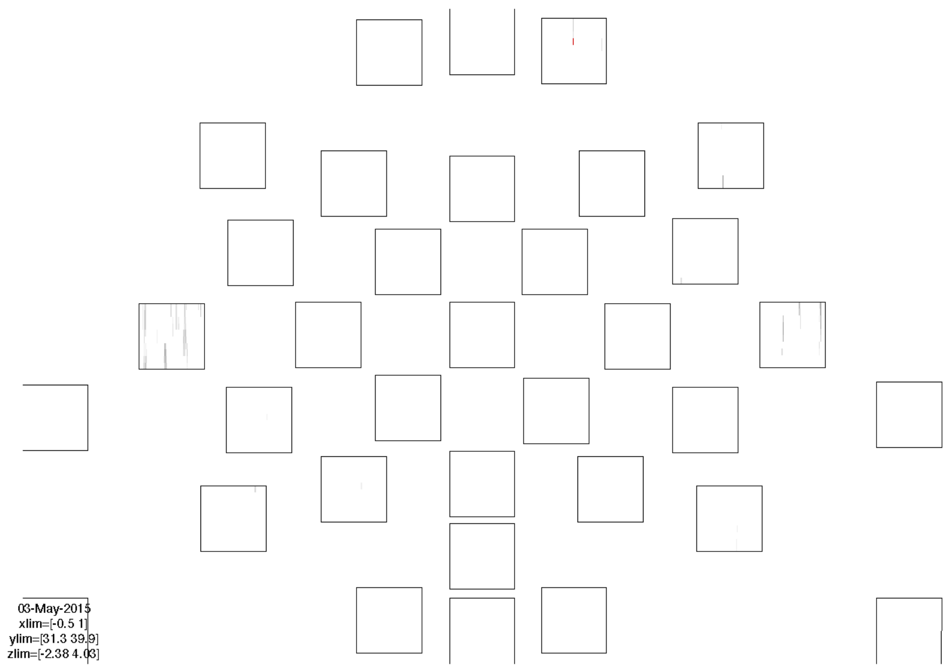


Figure A.20: Reanalysis with subset of subjects (15), Verb Agreement Violation: Gamma band (31-40Hz) masked stats TFR, significant channels

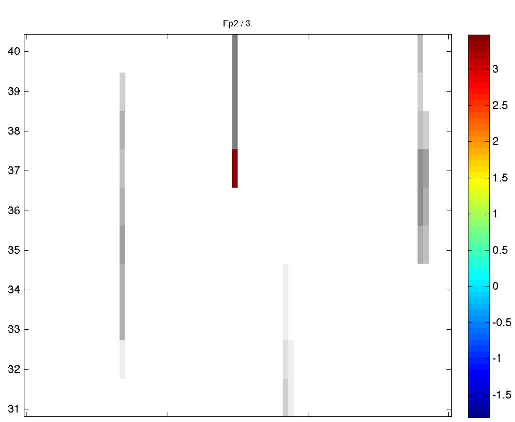
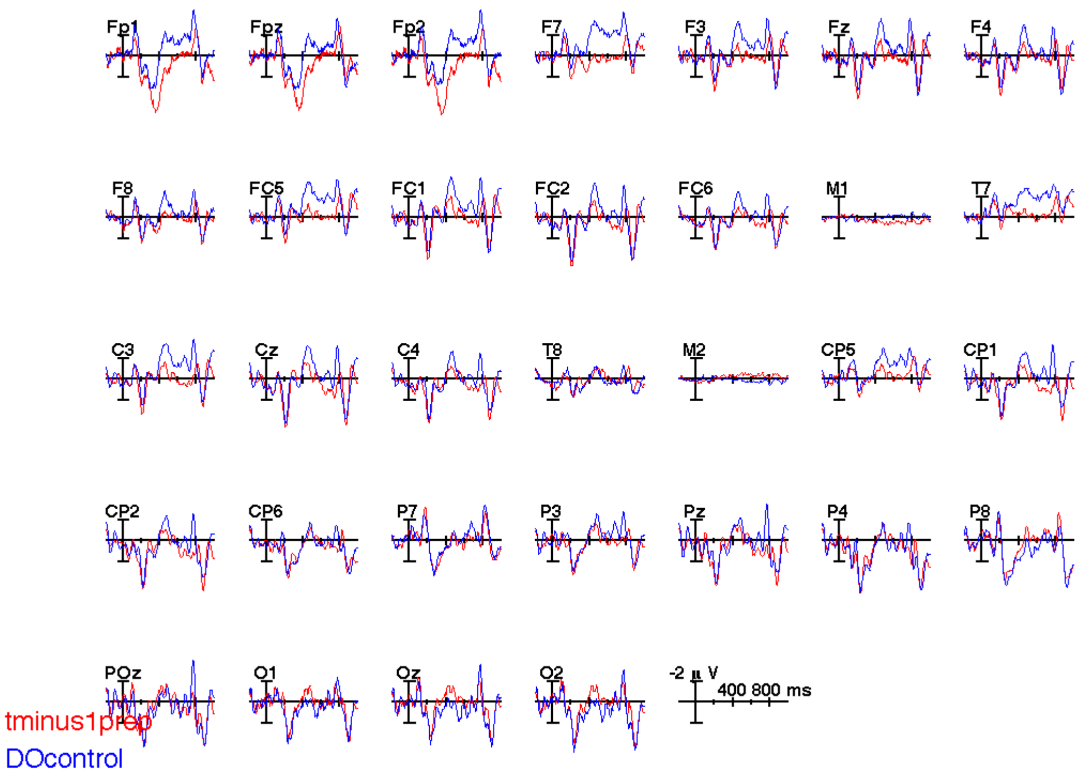


Figure A.21: Reanalysis with subset of subjects (15), θ-Criterion Violation: ERPs



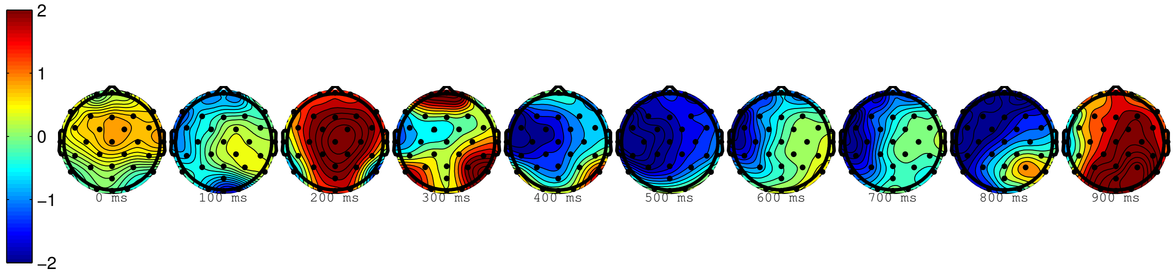
Reanalysis with subset of subjects (15): θ-Criterion Violation

CONTROL	The cameraman knew *that the* former mayor would *honor* *the* soldiers before the fireworks.
θ-VIOLATION	The cameraman knew that the former mayor would honor *before* the fireworks.

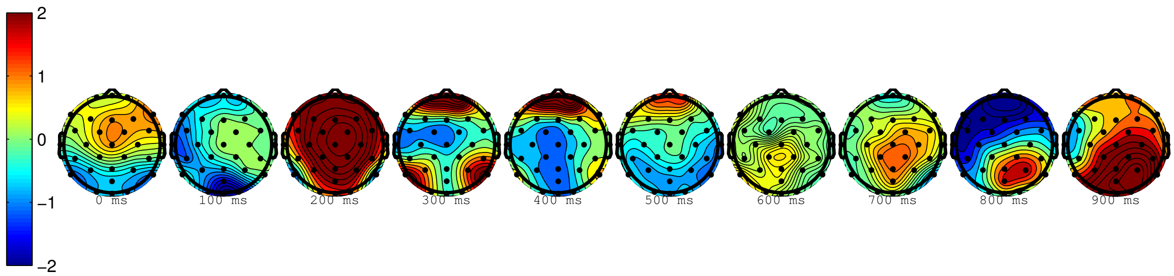
ERPs

Figure A.22: Reanalysis with subset of subjects (15), θ-Criterion Violation: topoplots

DO Control



θ-Criterion Violation



Difference plots

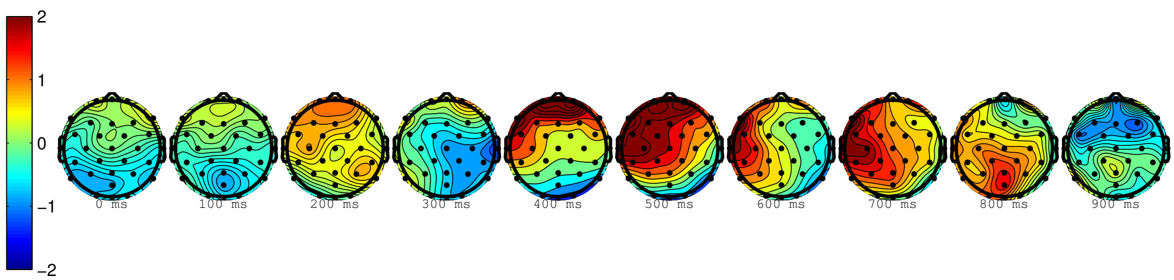


Figure A.23: Reanalysis with subset of subjects (15), θ-Criterion Violation: t_{max} permutation tests

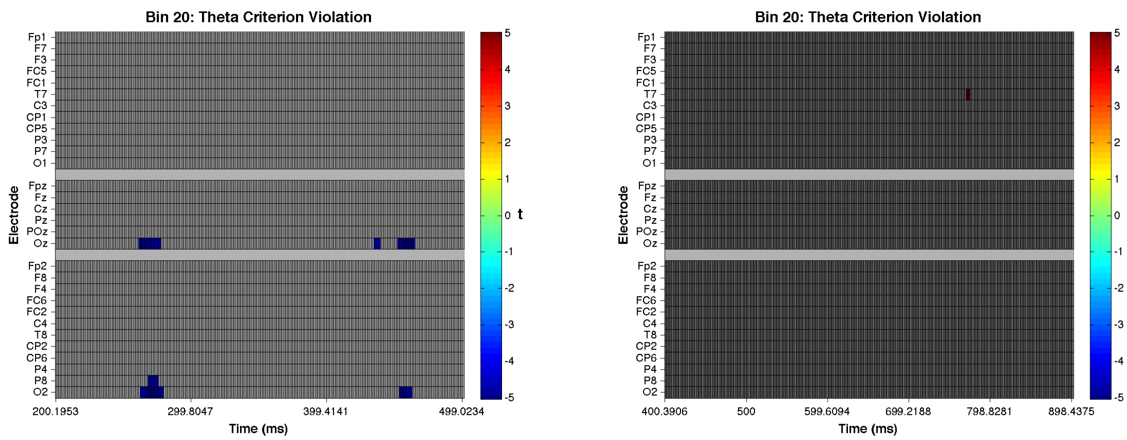


Figure A.24: Reanalysis with subset of subjects (15), θ-Criterion Violation: cluster mass permutation tests

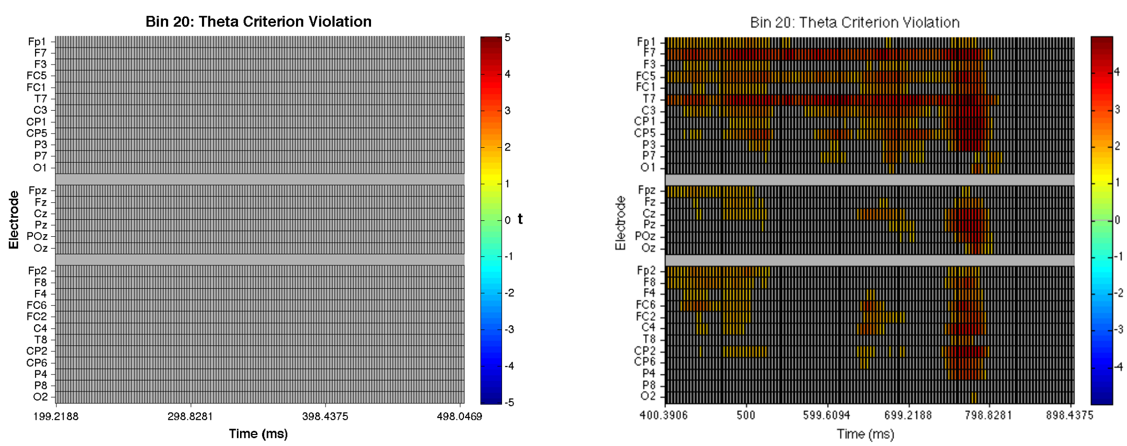
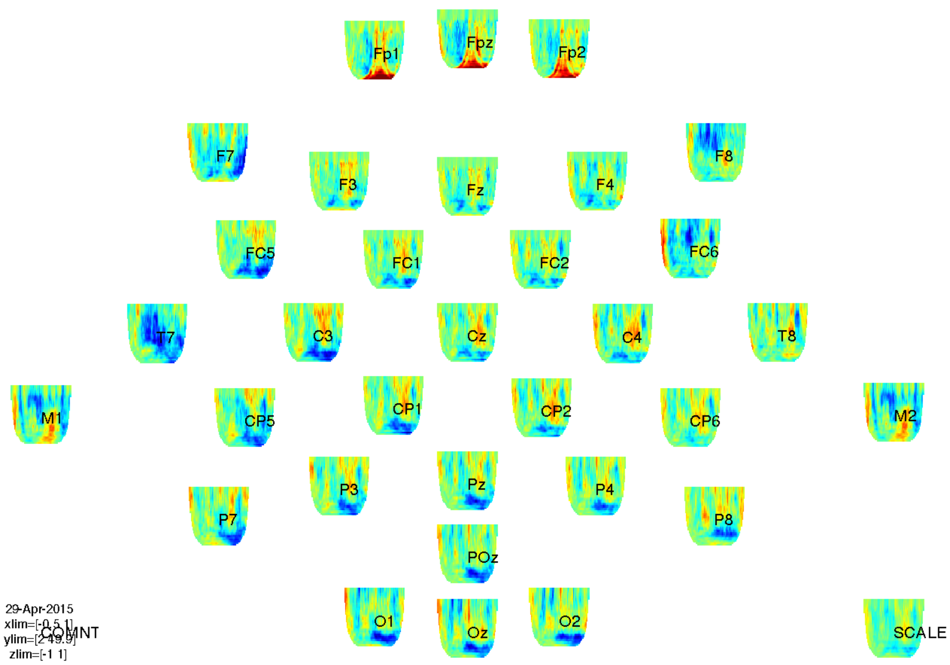


Figure A.25: Reanalysis with subset of subjects (15), θ-Criterion Violation: TFR



TFRs

Figure A.26: Reanalysis with subset of subjects (15), θ-Criterion Violation: Alpha band (8-12Hz) masked stats TFR

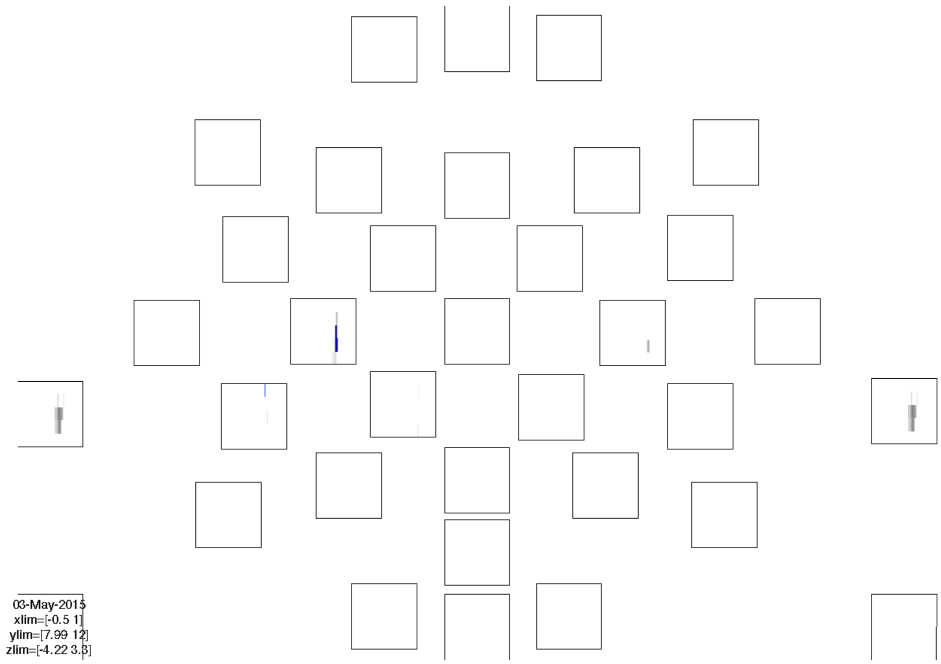


Figure A.27: Reanalysis with subset of subjects (15), θ-Criterion: Alpha band (8-12Hz) masked stats TFR, significant channels

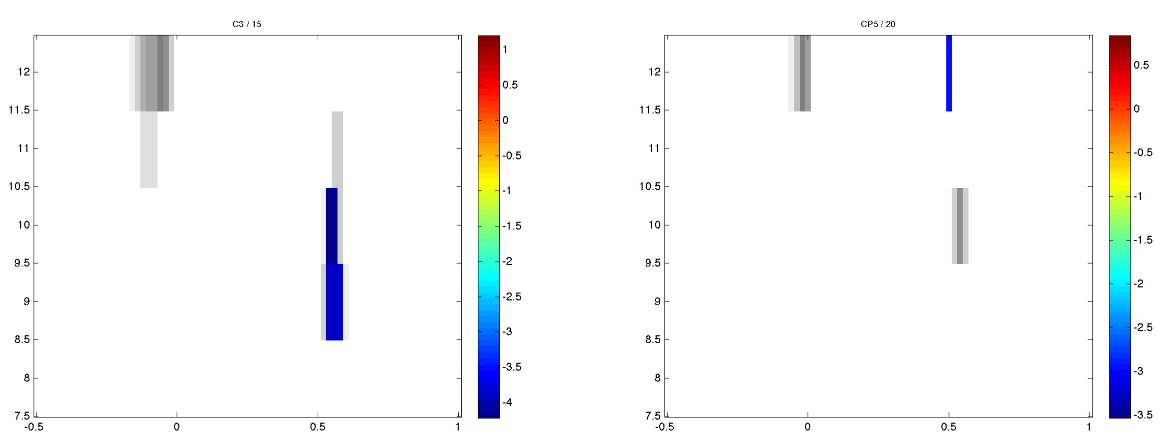


Figure A.28: Reanalysis with subset of subjects (15), θ-Criterion Violation: Lower Beta band (13-20Hz) masked stats TFR

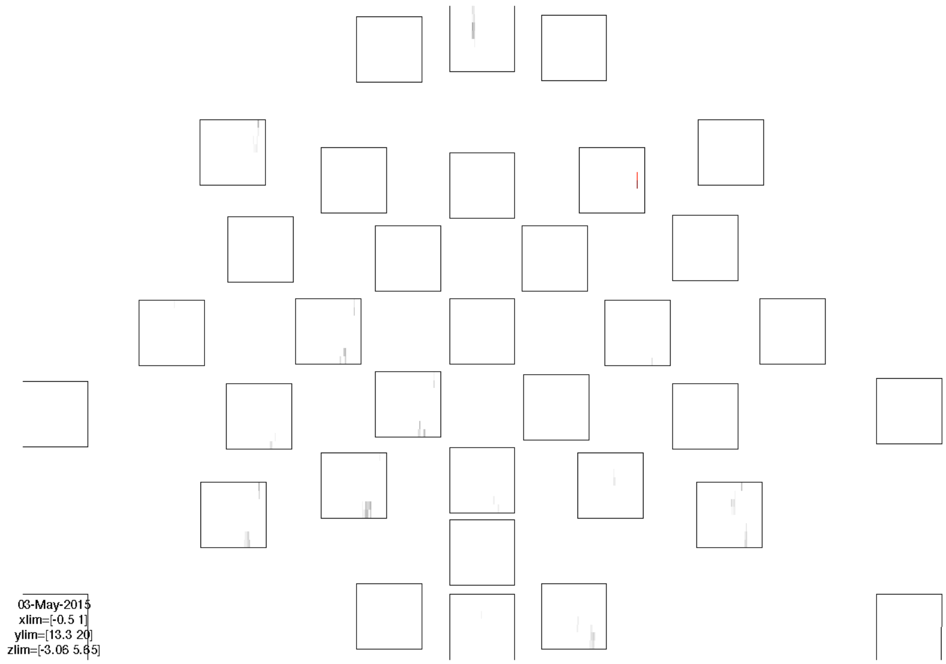


Figure A.29: Reanalysis with subset of subjects (15), θ-Criterion Violation: Lower Beta band (13-20Hz) masked stats TFR, significant channels

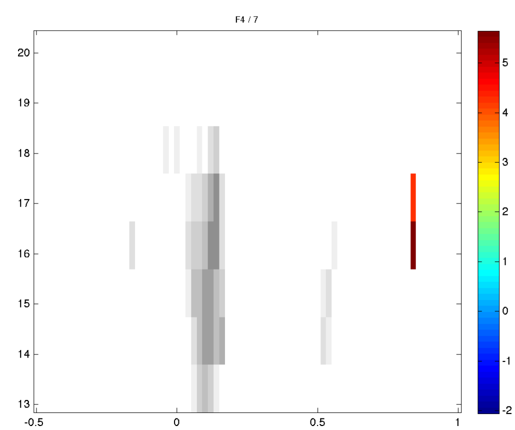


Figure A.30: Reanalysis with subset of subjects (15), θ-Criterion Violation: Upper Beta band (21-30Hz) masked stats TFR

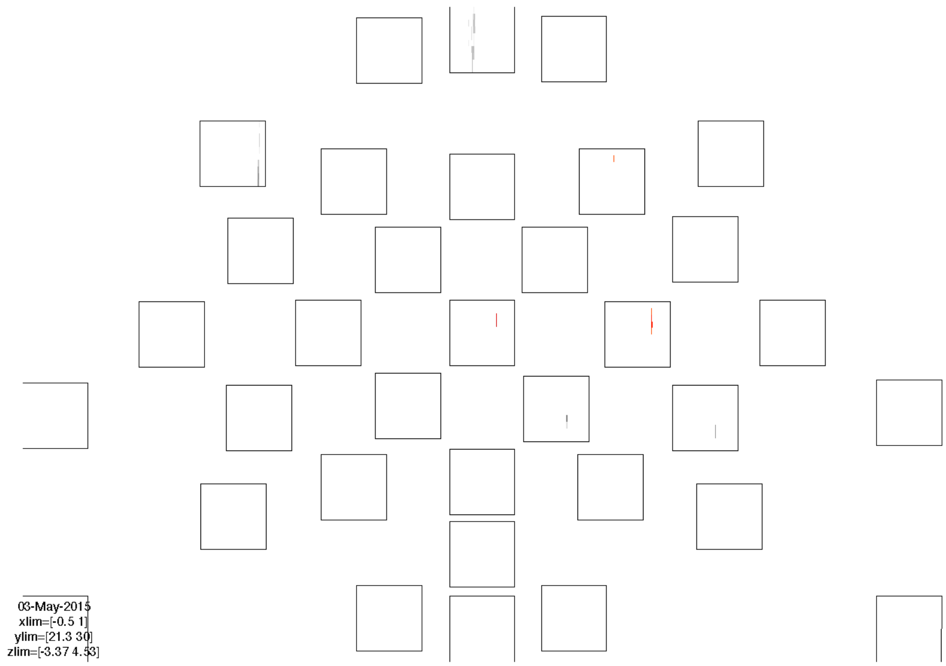


Figure A.31: Reanalysis with subset of subjects (15), θ-Criterion Violation: Upper Beta band (21-30Hz) masked stats TFR, significant channels

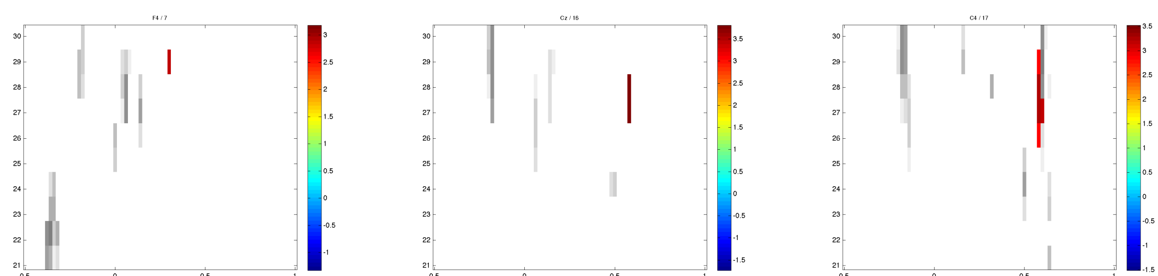


Figure A.32: Reanalysis with subset of subjects (15), θ-Criterion Violation: Gamma band (31-40Hz) masked stats TFR

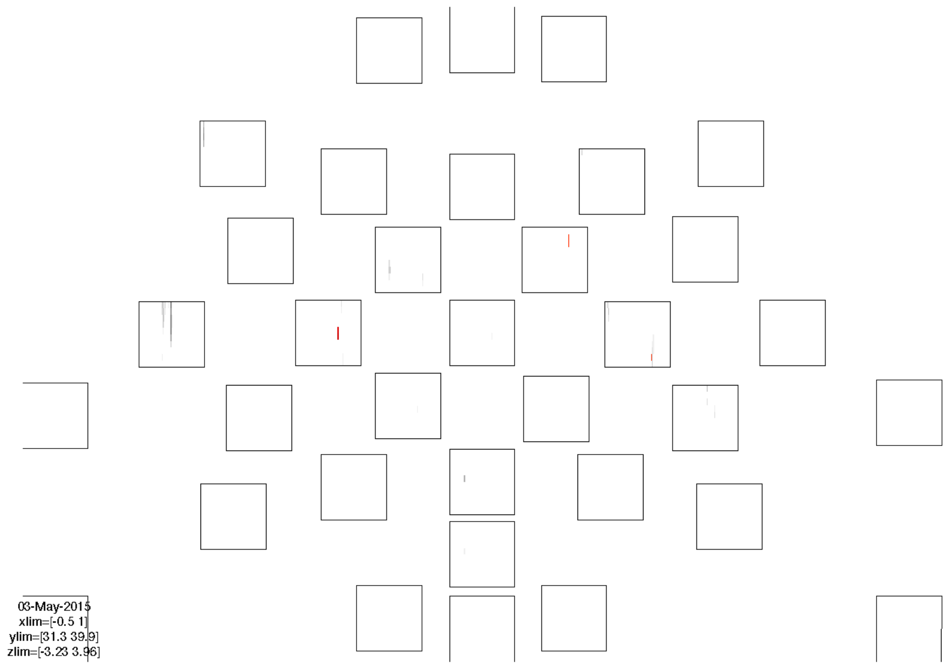


Figure A.33: Reanalysis with subset of subjects (15), θ-Criterion Violation: Gamma band (31-40Hz) masked stats TFR, significant channels

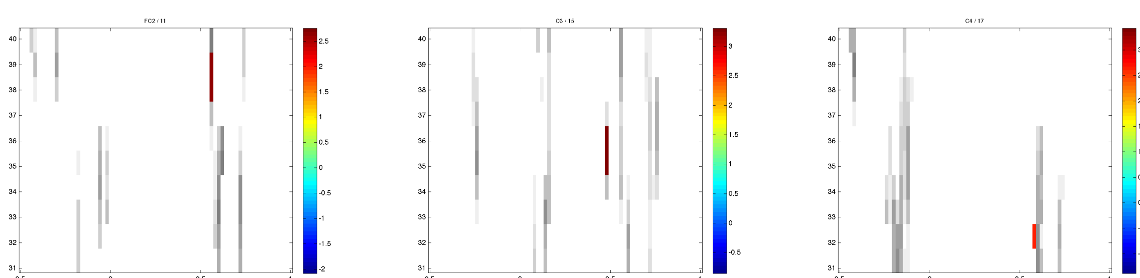
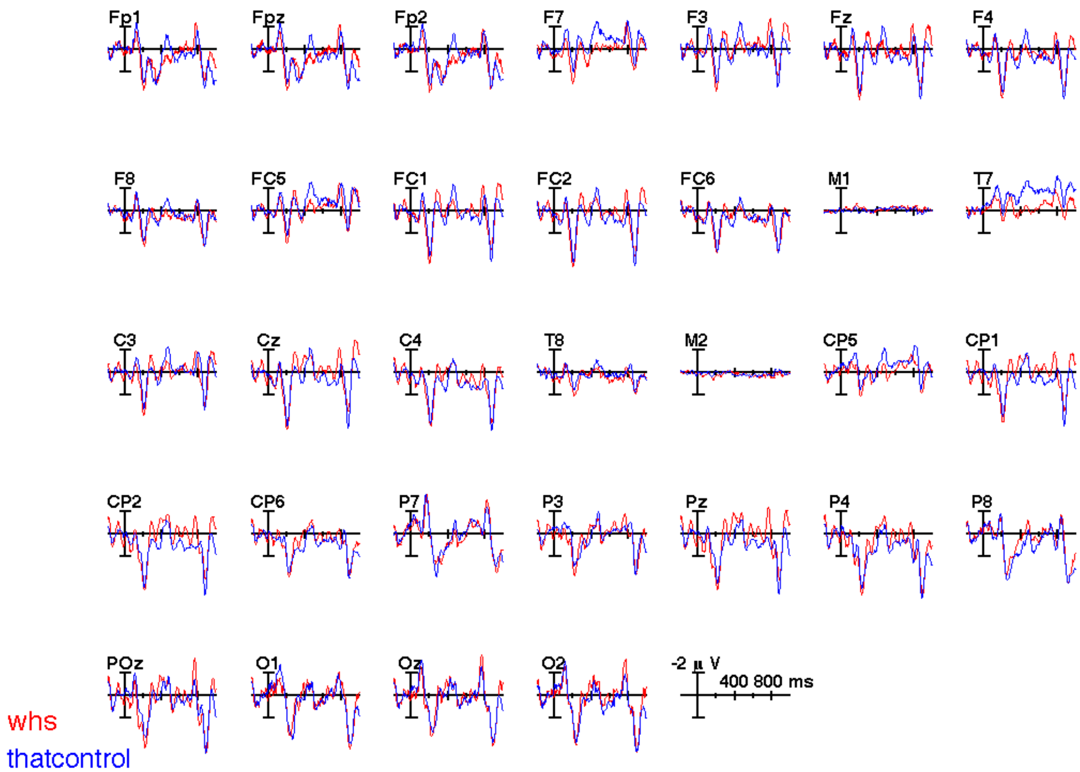


Figure A.34: Reanalysis with subset of subjects (15), 'Who', Short-distance dependency vs. *that*, Control: ERPs



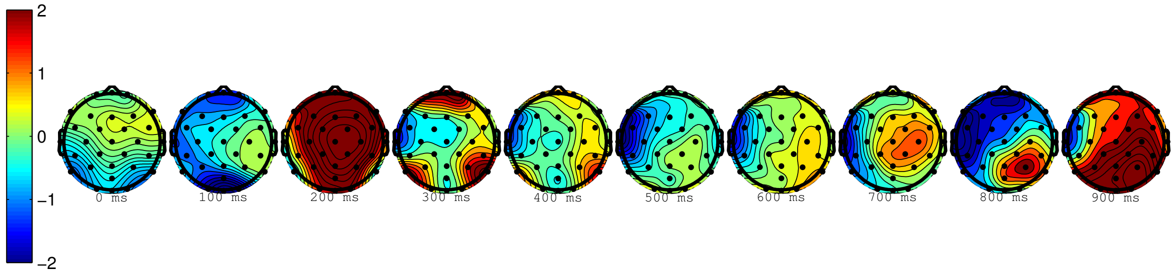
Reanalysis with subset of subjects (15): Short-distance dependency vs. Control: *wh*-filler

CONTROL	The cameraman knew *that* *the* former mayor would *honor* *the* soldiers before the fireworks.
WHS	The cameraman knew *who* *would* honor the soldiers before *the* fireworks.

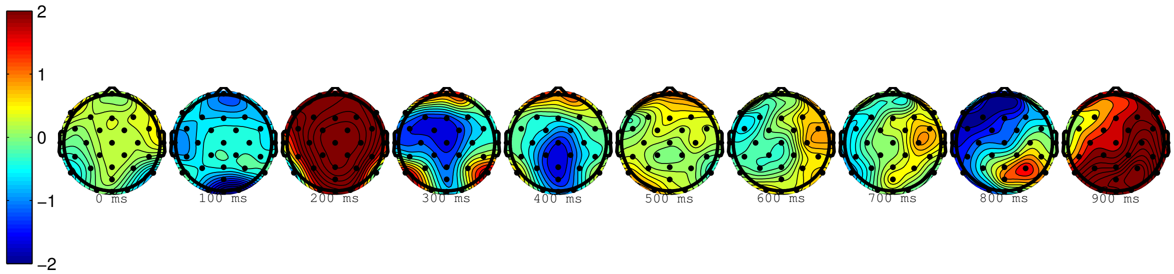
ERPs

Figure A.35: Reanalysis with subset of subjects (15), 'Who', Short-distance dependency vs. *that*, Control: topoplots

that Control



Who, Short-distance dependency



Difference plots

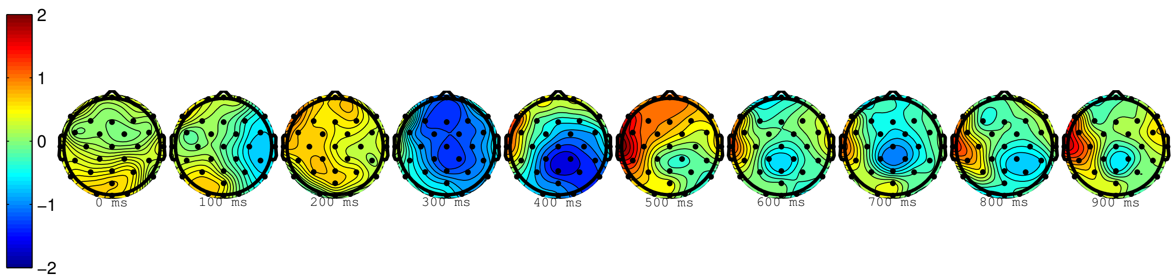


Figure A.36: Reanalysis with subset of subjects (15), 'Who', Short-distance dependency vs. *that*, Control: t_{max} permutation tests

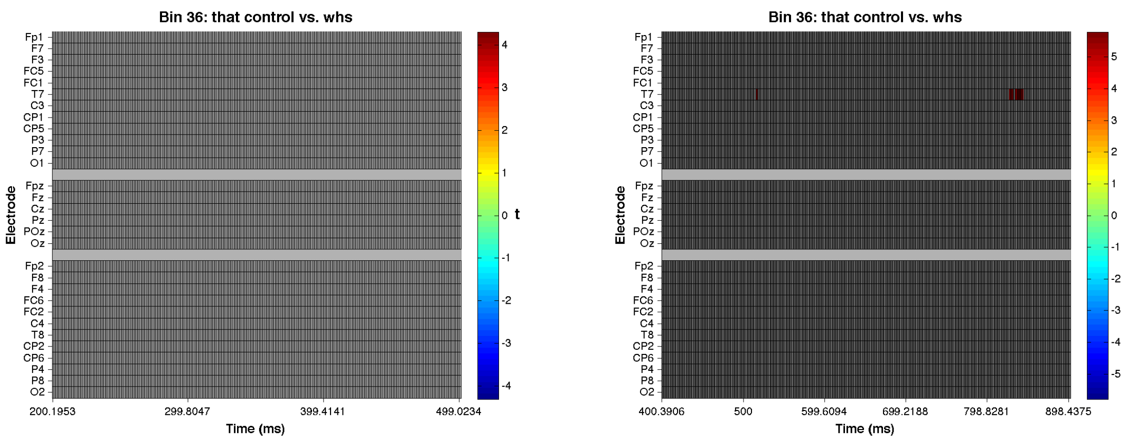


Figure A.37: Reanalysis with subset of subjects (15), 'Who', Short-distance dependency vs. *that*, Control: cluster mass permutation tests

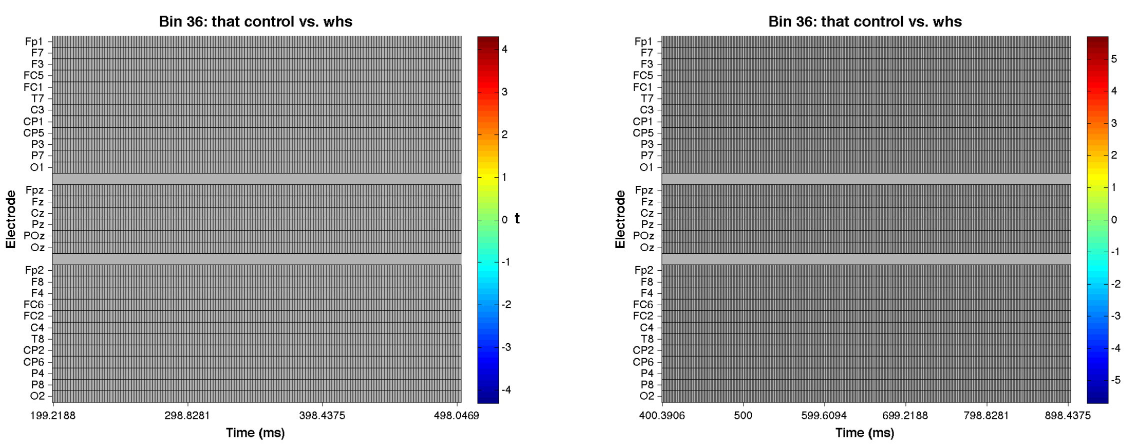
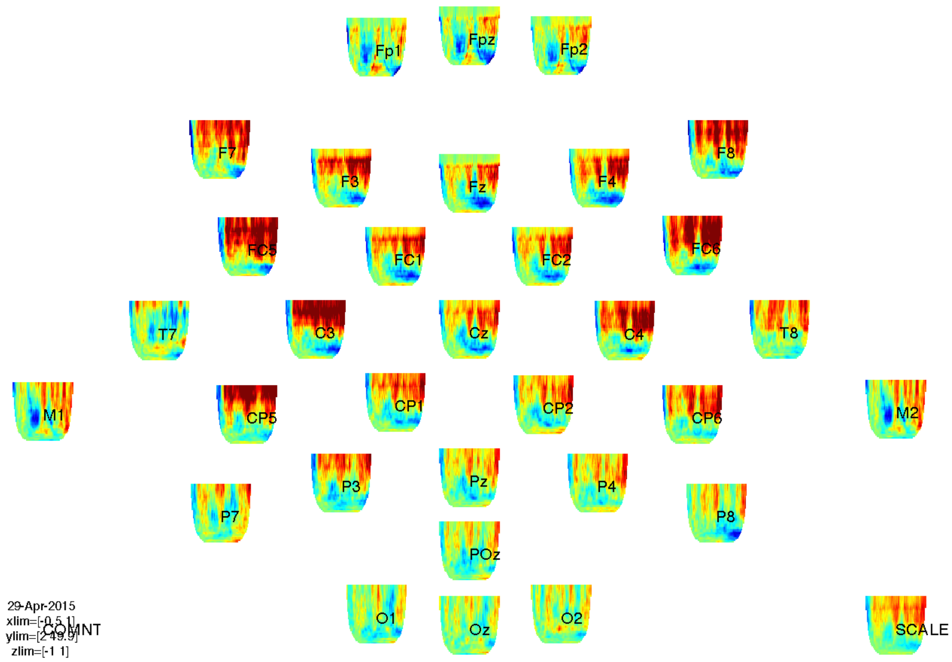


Figure A.38: Reanalysis with subset of subjects (15), Short-distance dependency, *wh*-filler: TFR



TFRs

Figure A.39: Reanalysis with subset of subjects (15), Short-distance dependency, *wh*-filler: Lower Beta band (13-20Hz) masked stats TFR

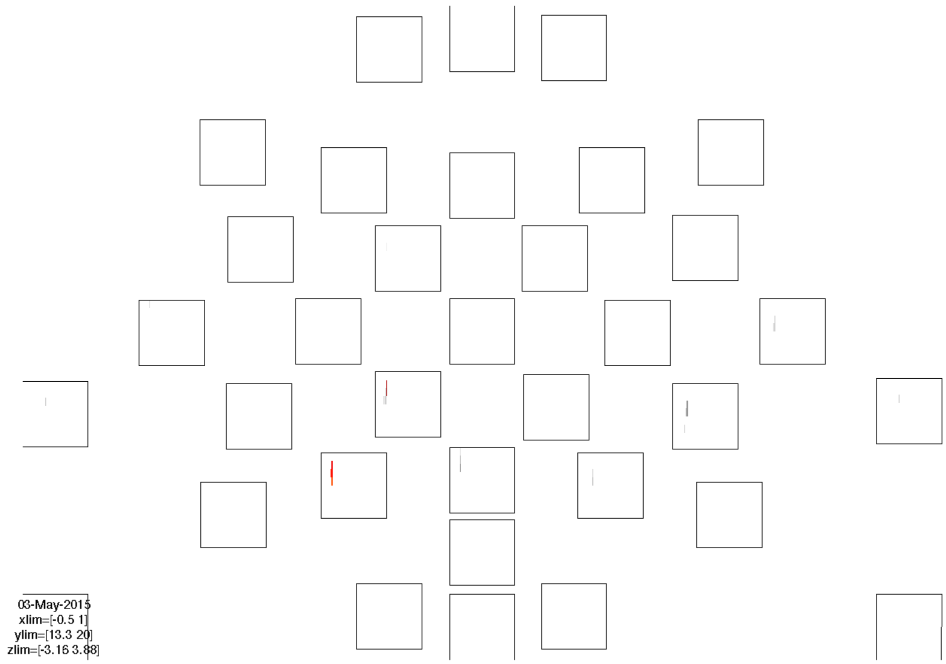


Figure A.40: Reanalysis with subset of subjects (15), Short-distance dependency, *wh*-filler: Lower Beta band (13-20Hz) masked stats TFR, significant channels

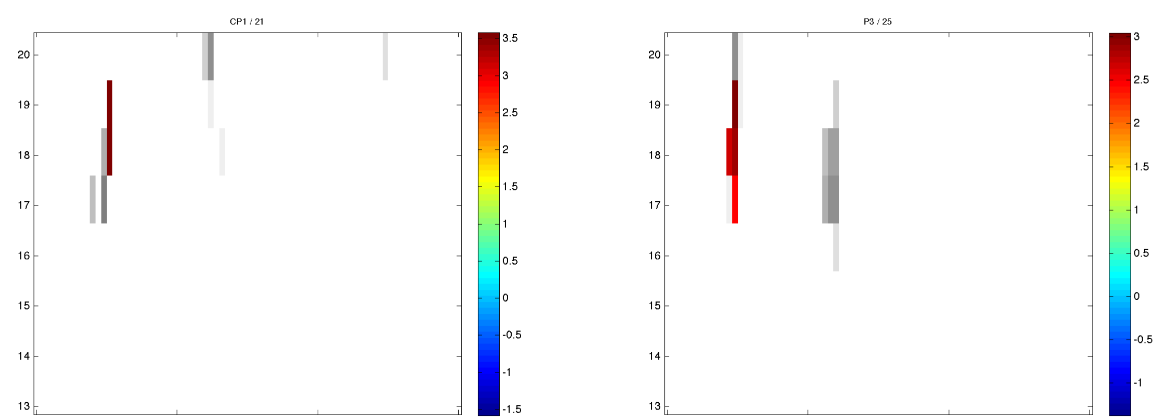


Figure A.41: Reanalysis with subset of subjects (15), Short-distance dependency, *wh*-filler: Upper Beta band (21-30Hz) masked stats TFR

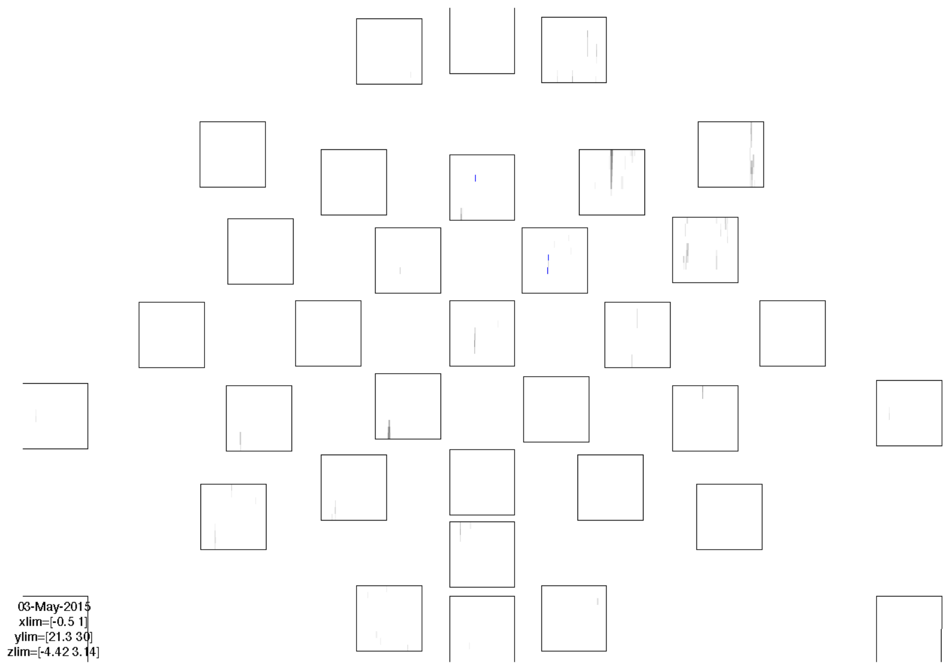


Figure A.42: Reanalysis with subset of subjects (15), Short-distance dependency, *wh*-filler: Upper Beta band (21-30Hz) masked stats TFR, significant channels

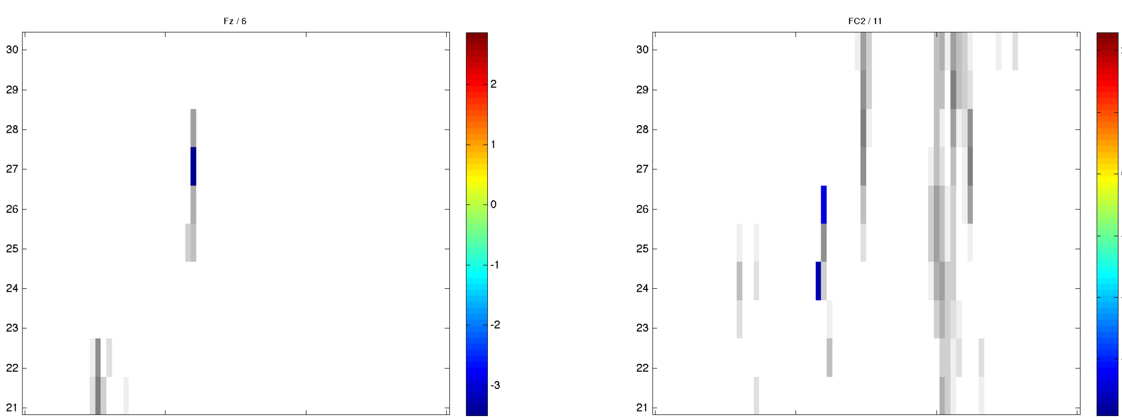
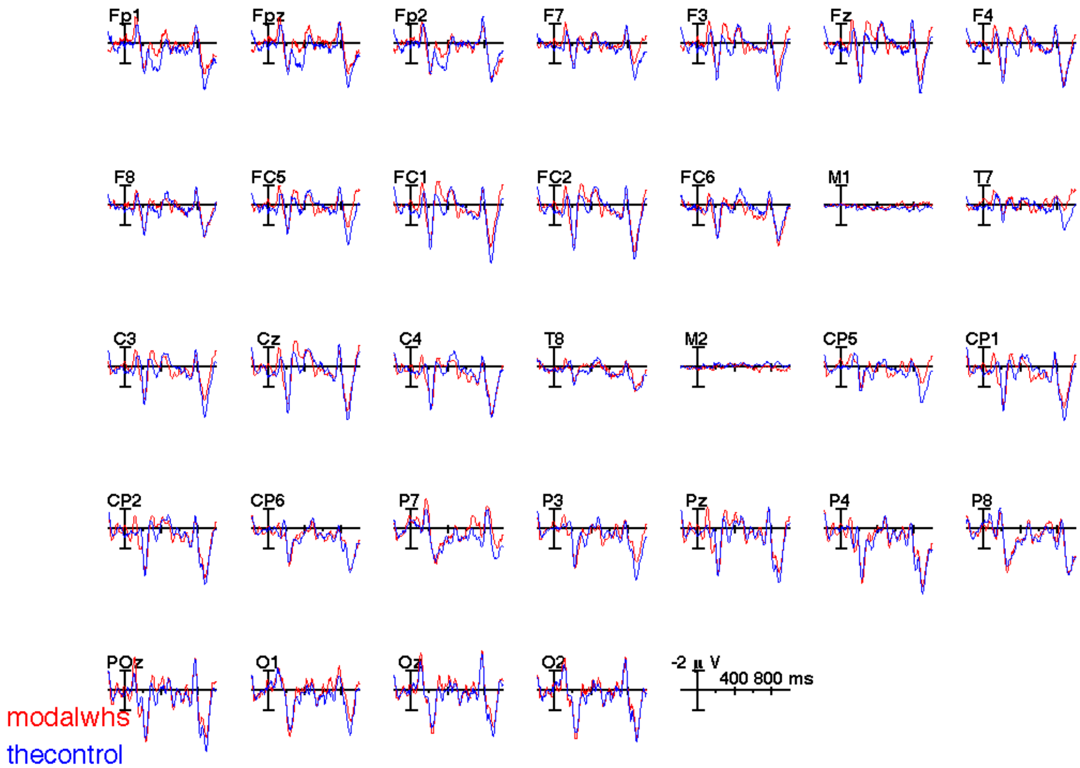


Figure A.43: Reanalysis with subset of subjects (15), Modal, Short-distance dependency vs. *the*, Control: ERPs



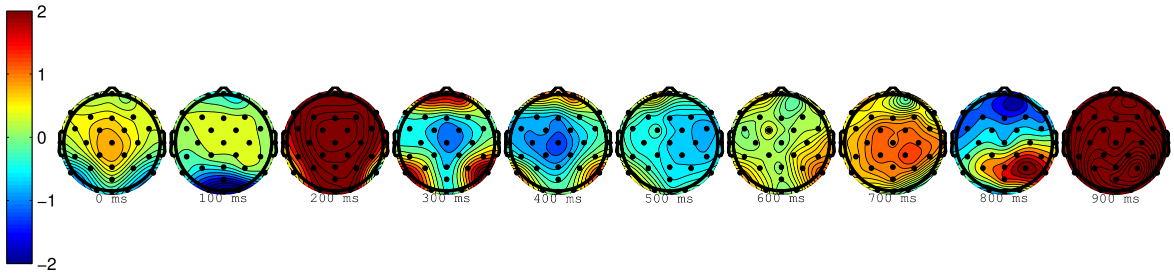
Reanalysis with subset of subjects (15), Short-distance dependency vs. Control: gap resolution

CONTROL	The cameraman knew *that* *the* former mayor would *honor* *the* soldiers before the fireworks.
WHS	The cameraman knew *who* *would* honor the soldiers before *the* fireworks.

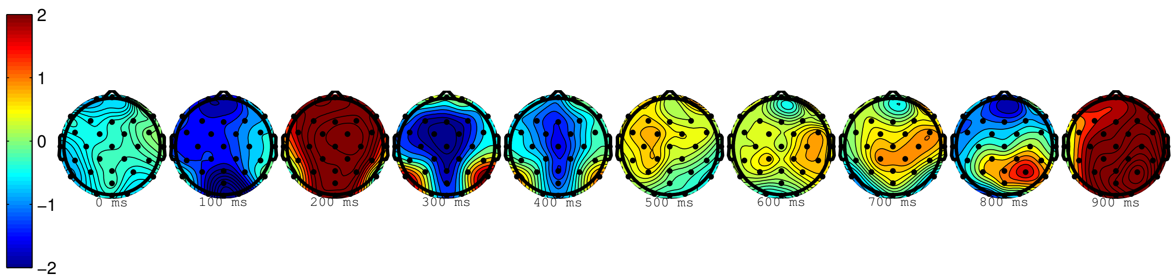
ERPs

Figure A.44: Reanalysis with subset of subjects (15), Modal, Short-distance dependency vs. *the*, Control: topoplots

the Control



Modal, Short-distance dependency



Difference plots

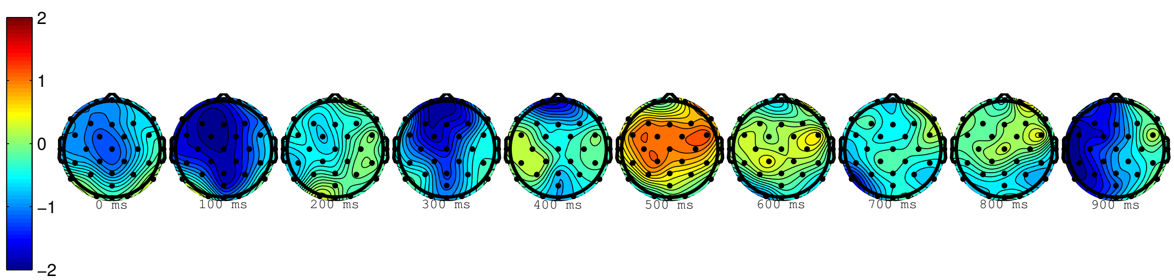


Figure A.45: Reanalysis with subset of subjects (15), Modal, Short-distance dependency vs. *the*, Control: t_{max} permutation tests

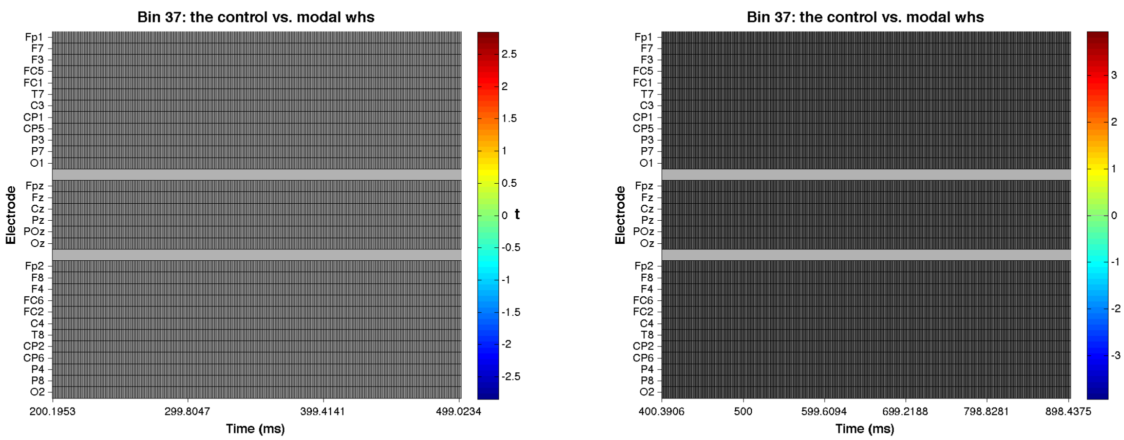
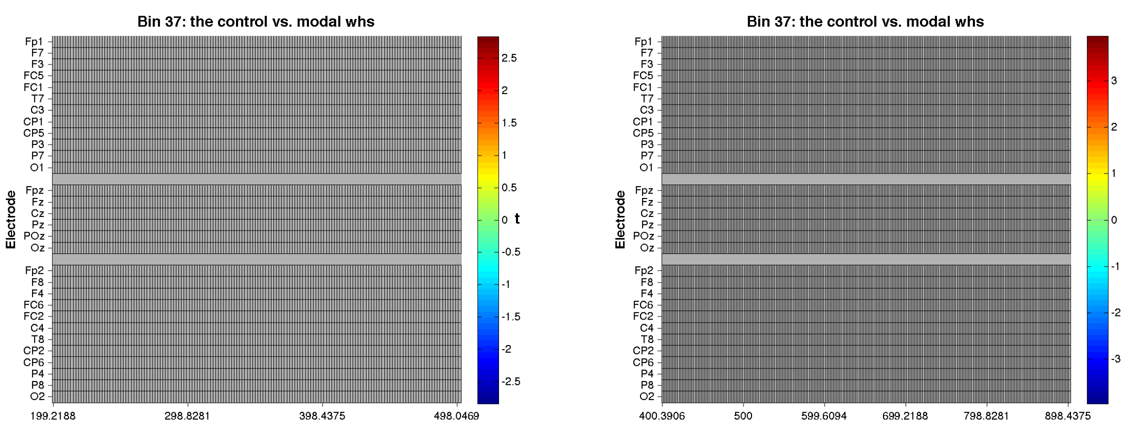


Figure A.46: Reanalysis with subset of subjects (15), Modal, Short-distance dependency vs. *the*, Control: cluster mass permutation tests



TFRs

Figure A.47: Reanalysis with subset of subjects (15), Short-distance dependency, gap resolution: TFR

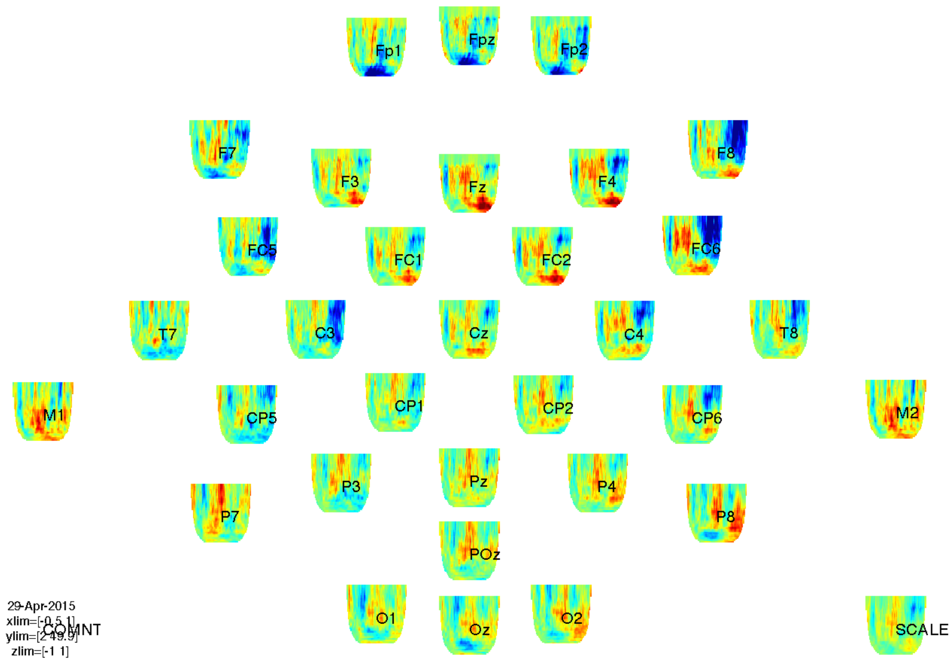


Figure A.48: Reanalysis with subset of subjects (15), Short-distance dependency, gap resolution: Gamma band (31-40Hz) masked stats TFR

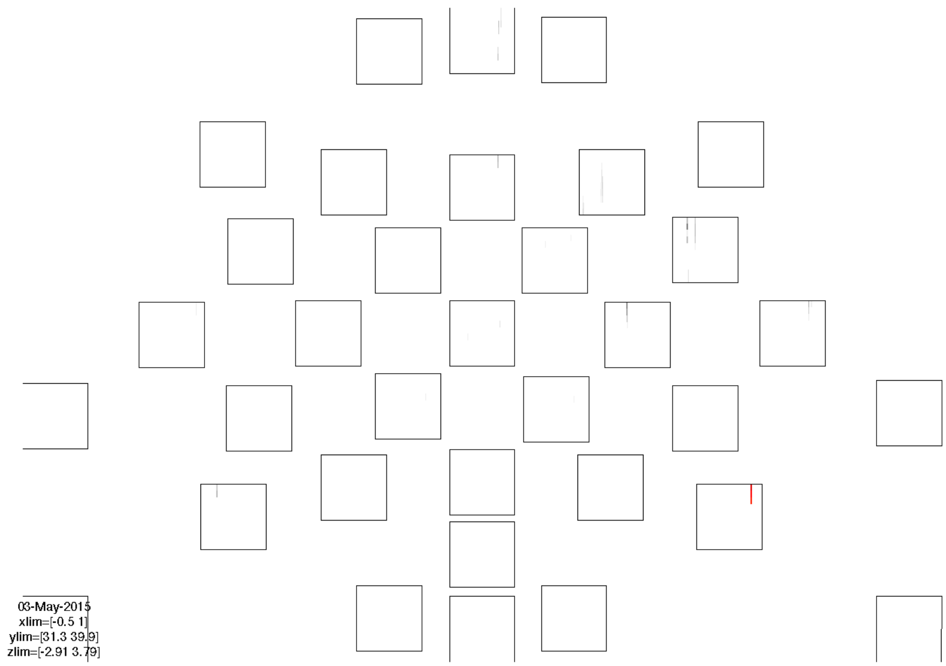


Figure A.49: Reanalysis with subset of subjects (15), Short-distance dependency, gap resolution: Gamma band (31-40Hz) masked stats TFR, significant channels

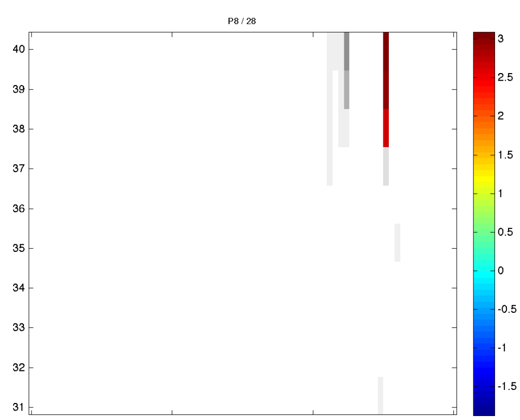
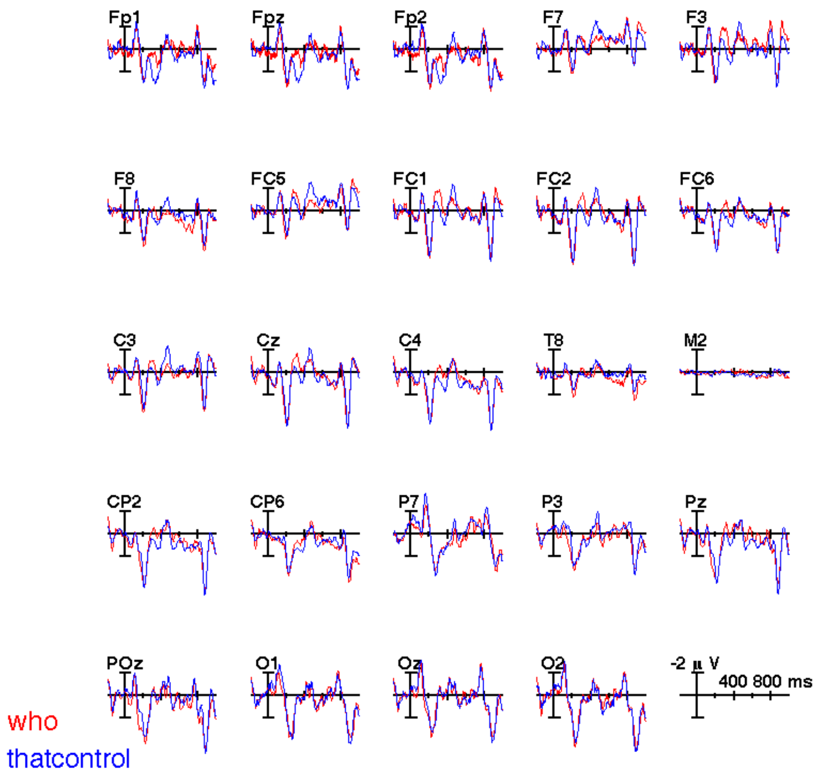


Figure A.50: Reanalysis with subset of subjects (15), 'Who', Long-distance dependency vs. *that* control: ERPs



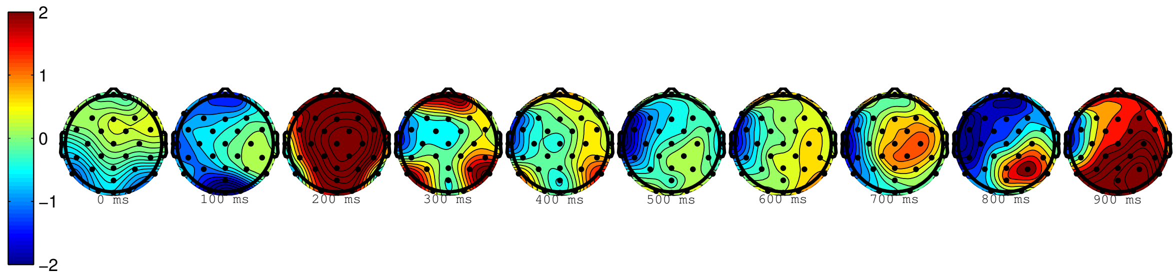
Reanalysis with subset of subjects (15), Long-distance dependency vs. Control: *wh*-filler

CONTROL	The cameraman knew *that* *the* former mayor would *honor* *the* soldiers before the fireworks.
WHO	The cameraman knew *who* *the* former mayor would honor *before* the fireworks.

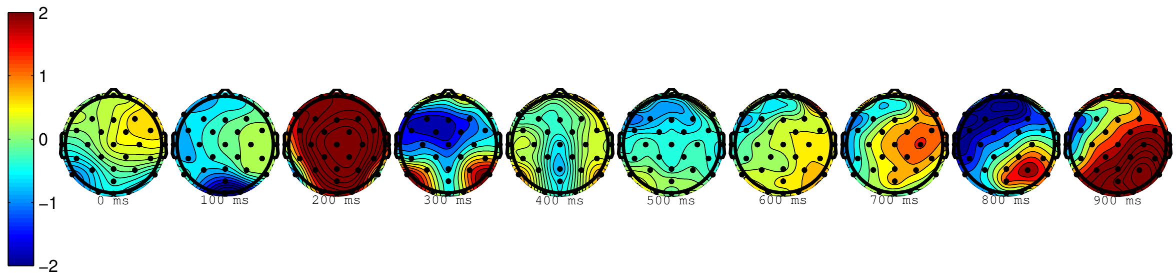
ERPs

Figure A.51: Reanalysis with subset of subjects (15), 'Who', Long-distance dependency vs. *that* control: topoplots

that control



Who, Long-distance dependency



Difference plots

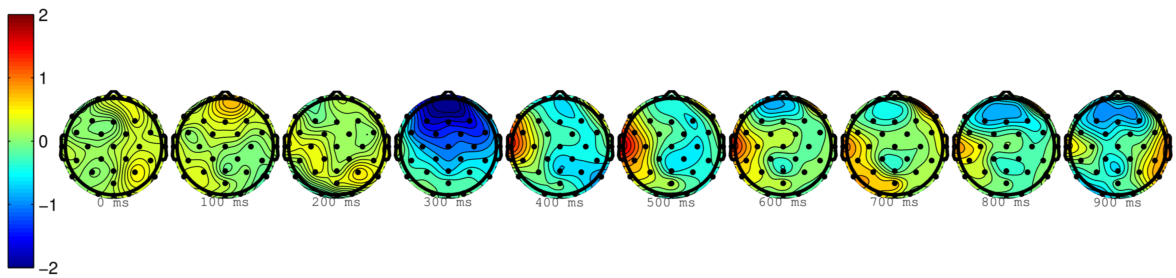


Figure A.52: Reanalysis with subset of subjects (15), 'Who', Long-distance dependency vs. *that* control: t_{max} tests

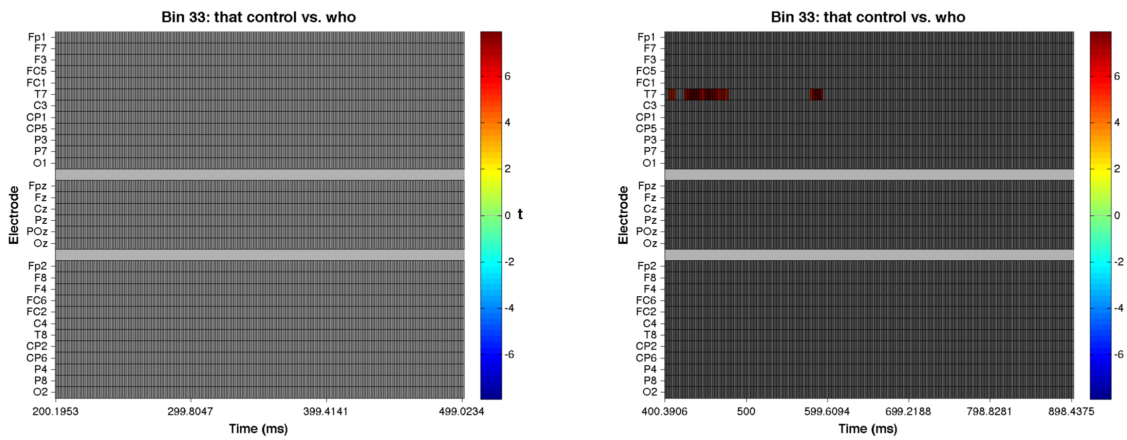


Figure A.53: Reanalysis with subset of subjects (15), 'Who', Long-distance dependency vs. *that* control: cluster mass permutation tests

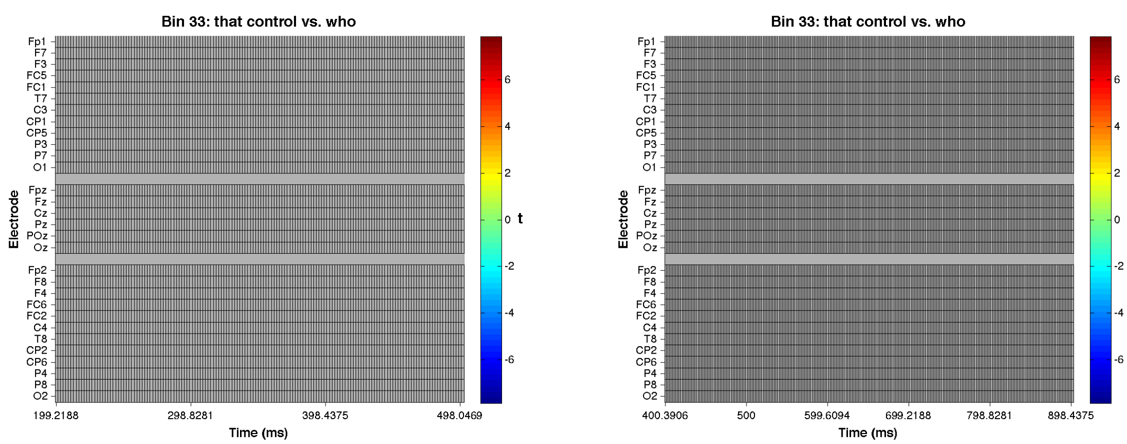
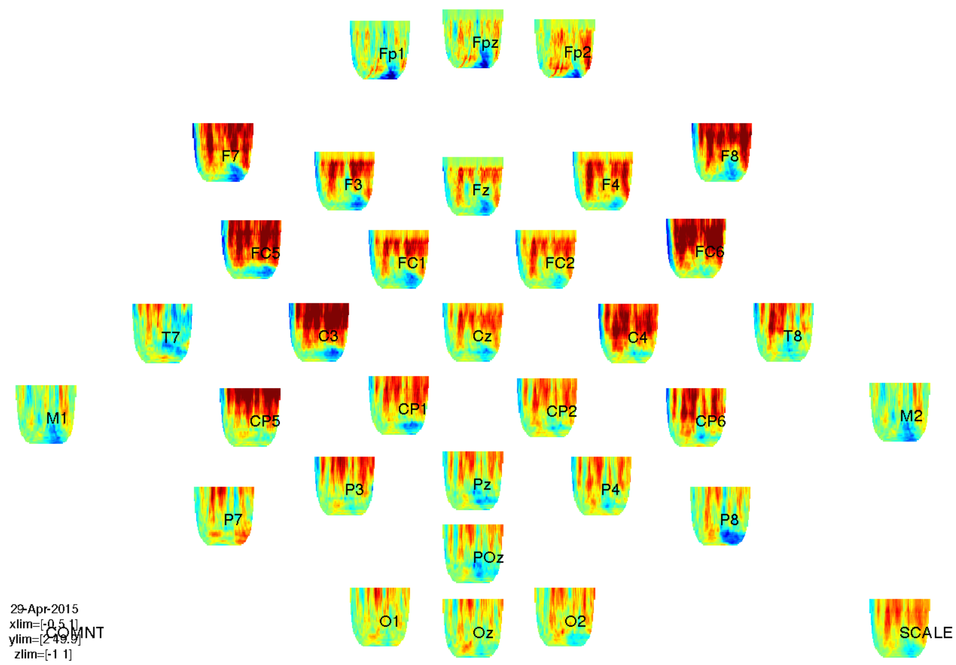
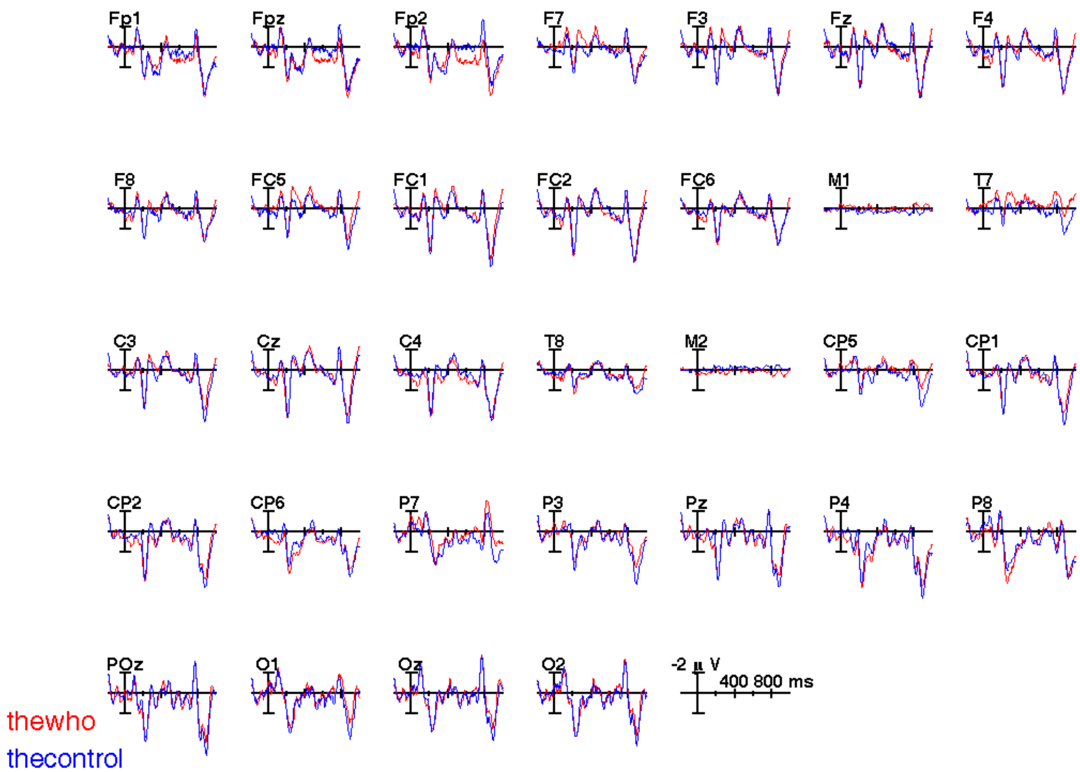


Figure A.54: Reanalysis with subset of subjects (15), Long-distance dependency, *wh*-filler: TFR



TFRs

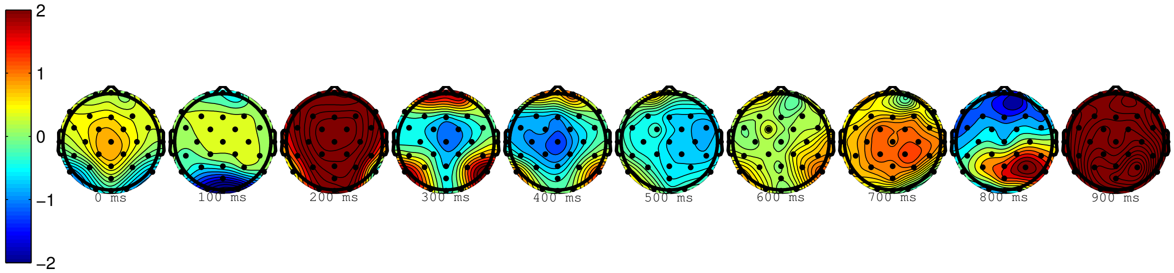
Figure A.55: Reanalysis with subset of subjects (15), *the*, Long-distance dependency vs. *the*, Control: ERPs



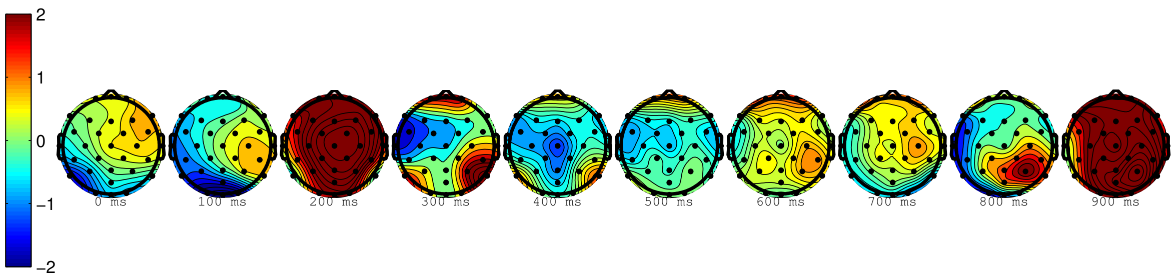
ERPs

Figure A.56: Reanalysis with subset of subjects (15), *the*, Long-distance dependency vs. *the*, Control: topoplots

the, Control



the, Long-distance dependency



Difference plots

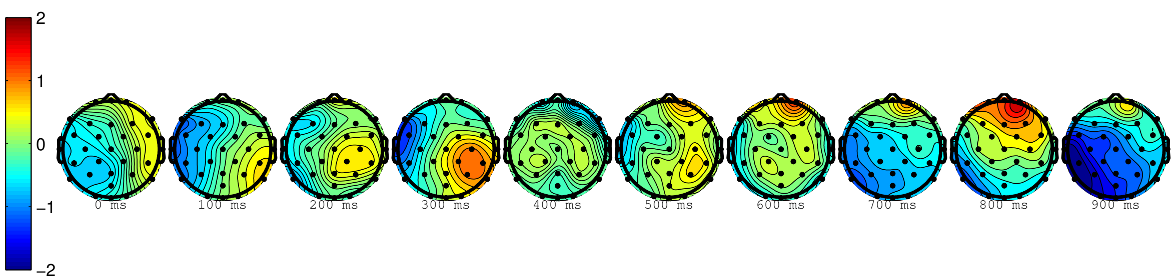


Figure A.57: Reanalysis with subset of subjects (15), *the*, Long-distance dependency vs. *the*, Control: t_{max} tests

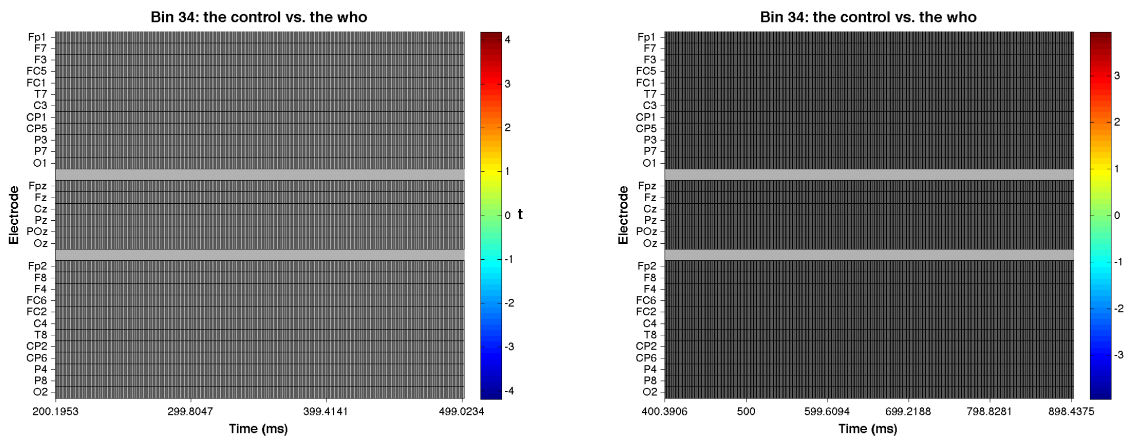
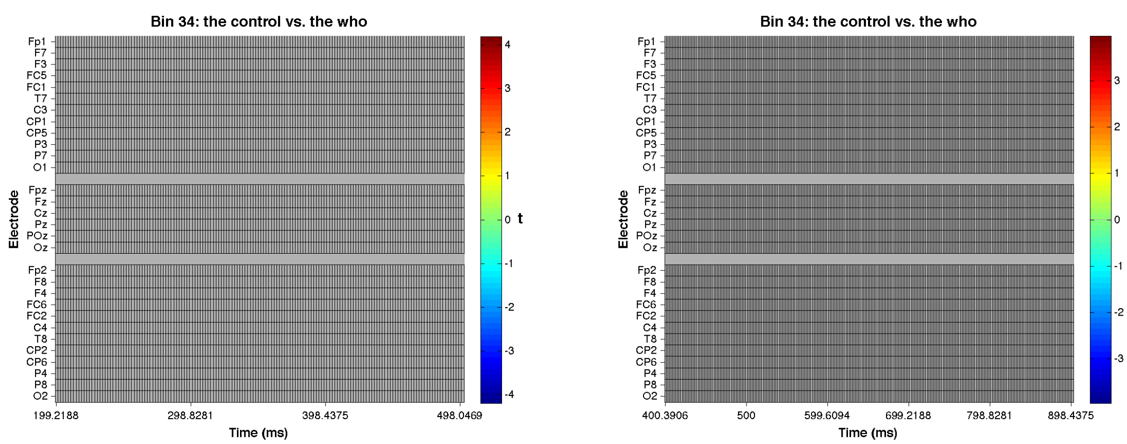


Figure A.58: Reanalysis with subset of subjects (15), *the*, Long-distance dependency vs. *the*, Control: cluster mass permutation tests



TFRs

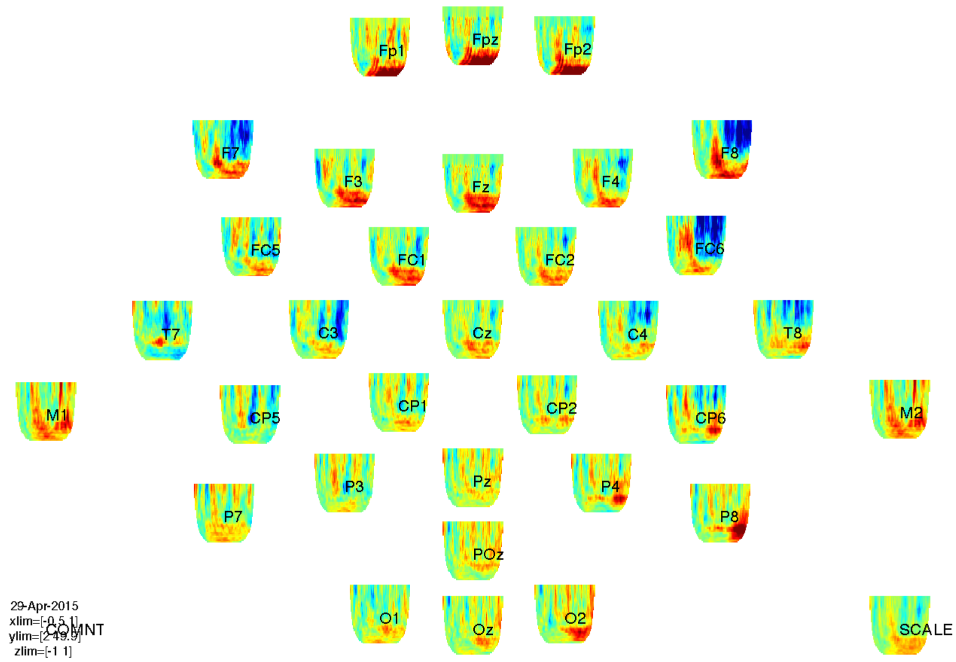


Figure A.59: Reanalysis with subset of subjects (15), *the*, Long-distance dependency vs. *the*, Control: TFR

Figure A.60: Reanalysis with subset of subjects (15), *the*, Long-distance dependency vs. *the*, Control: Lower Beta band (13-20Hz) masked stats TFR

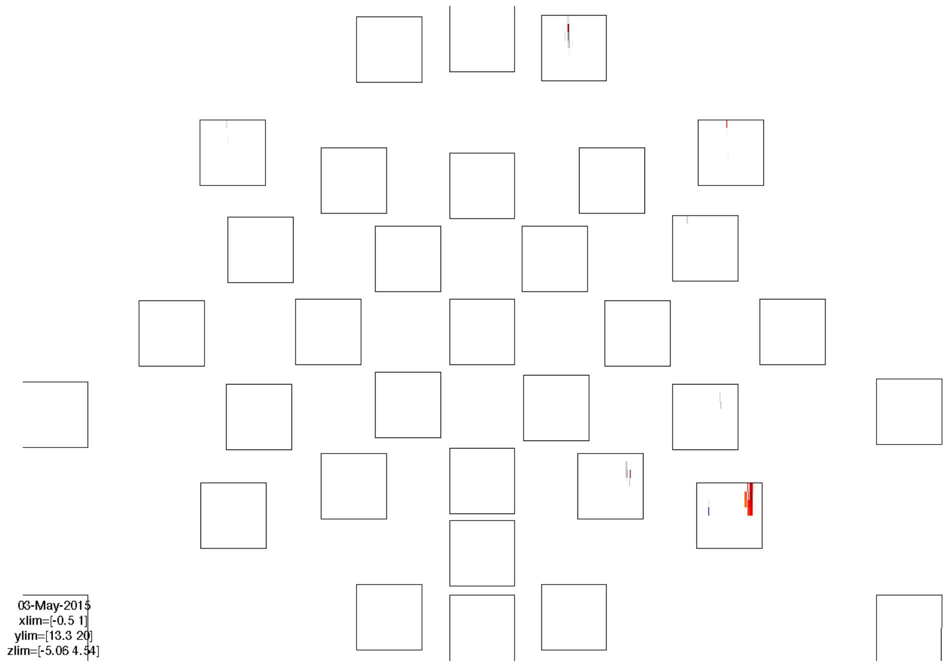


Figure A.61: Reanalysis with subset of subjects (15), *the*, Long-distance dependency vs. *the*, Control: Lower Beta band (13-20Hz) masked stats TFR, significant channels

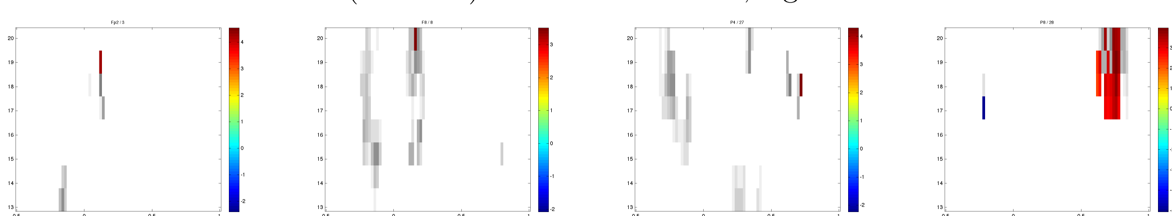


Figure A.62: Reanalysis with subset of subjects (15), *the*, Long-distance dependency vs. *the*, Control: Upper Beta band (21-30Hz) masked stats TFR

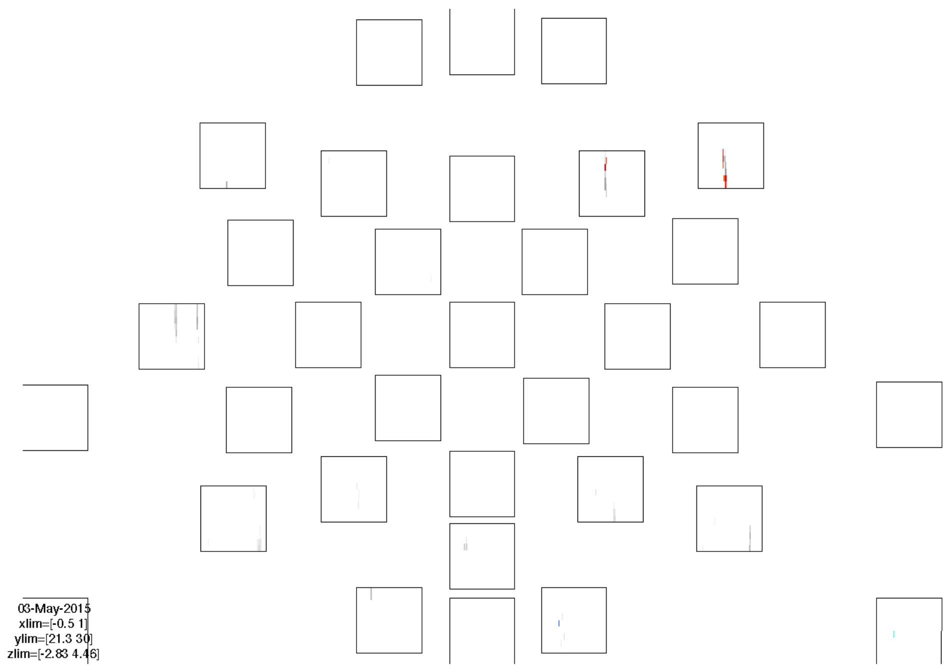


Figure A.63: Reanalysis with subset of subjects (15), *the*, Long-distance dependency vs. *the*, Control: Upper Beta band (21-30Hz) masked stats TFR, significant channels

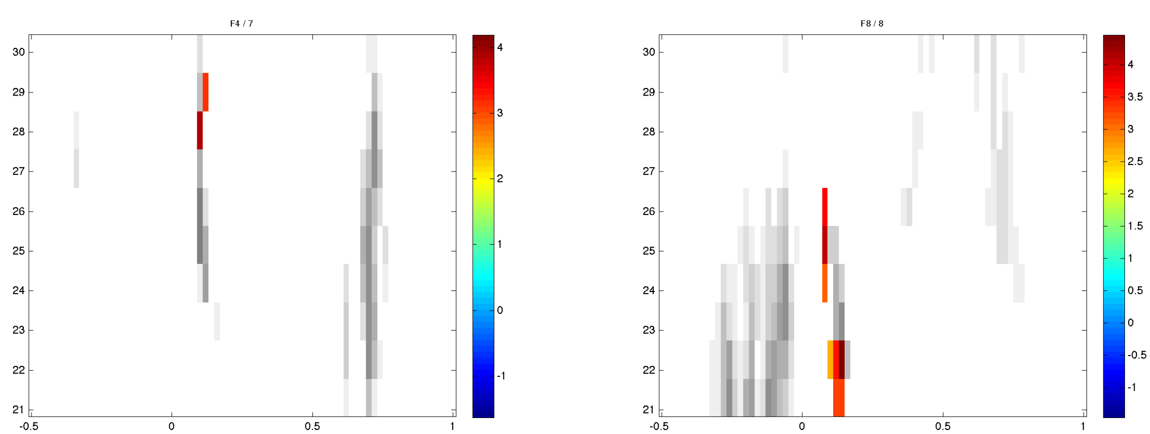


Figure A.64: Reanalysis with subset of subjects (15), *the*, Long-distance dependency vs. *the*, Control: Gamma band (31-40Hz) masked stats TFR

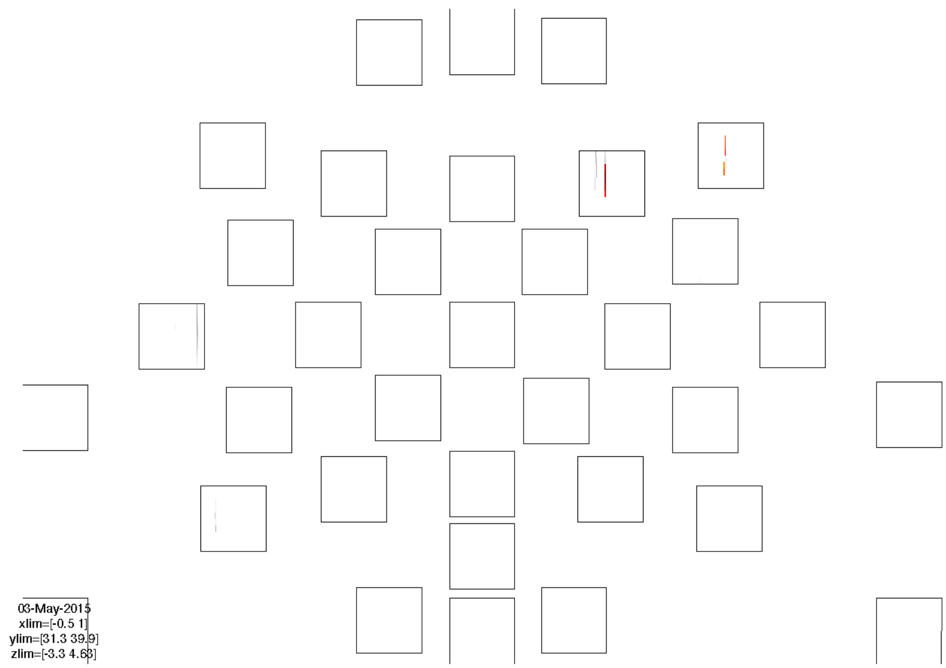


Figure A.65: Reanalysis with subset of subjects (15), *the*, Long-distance dependency vs. *the*, Control: Gamma band (31-40Hz) masked stats TFR, significant channels

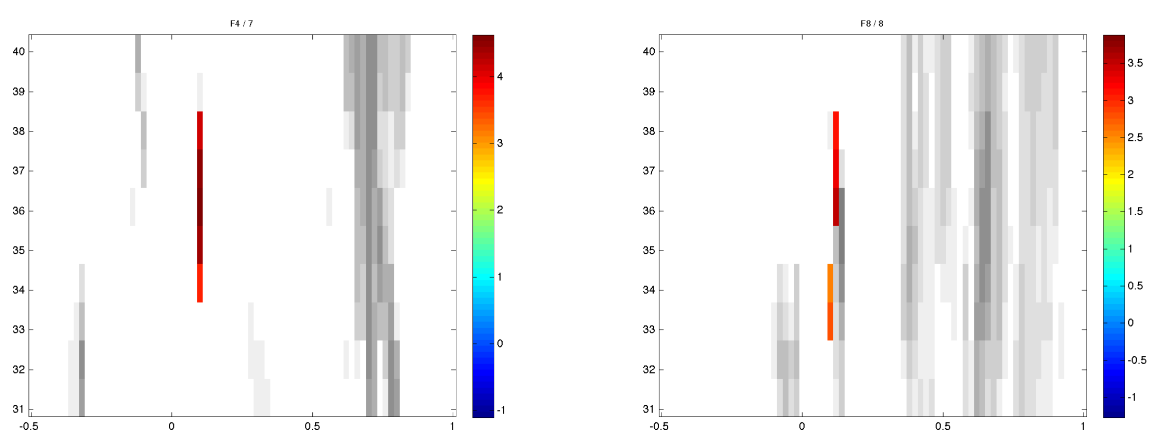
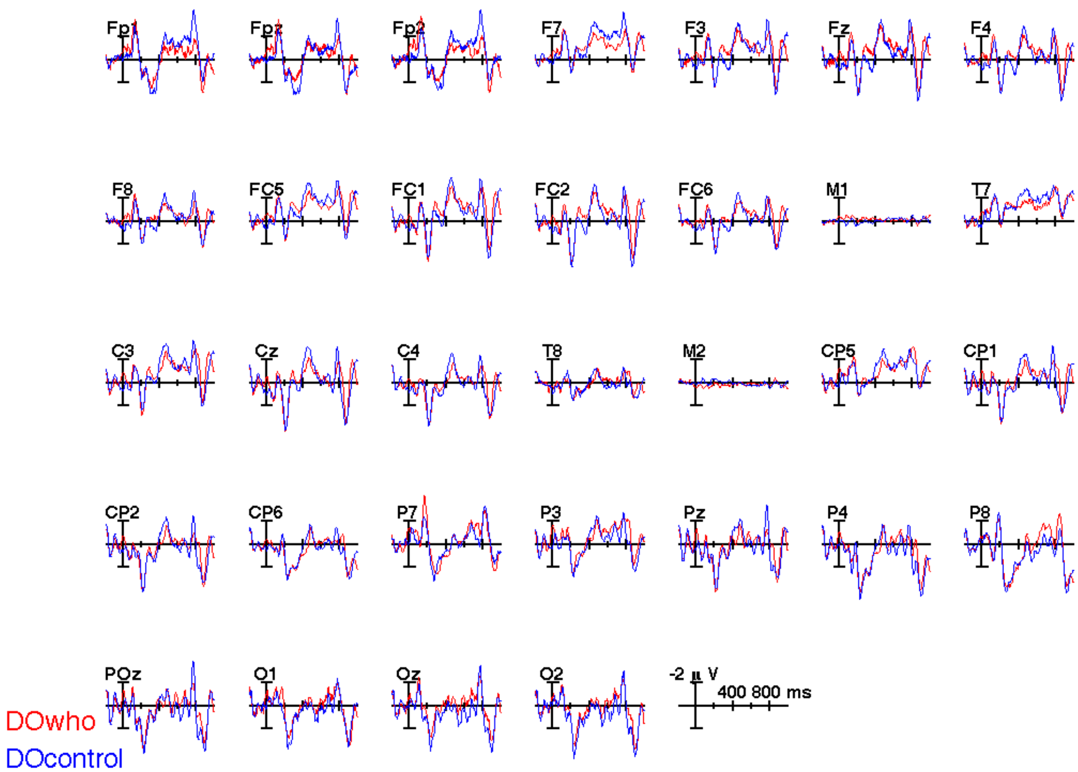


Figure A.66: Reanalysis with subset of subjects (15), PP, Long-distance dependency vs. DO, Control: ERPs



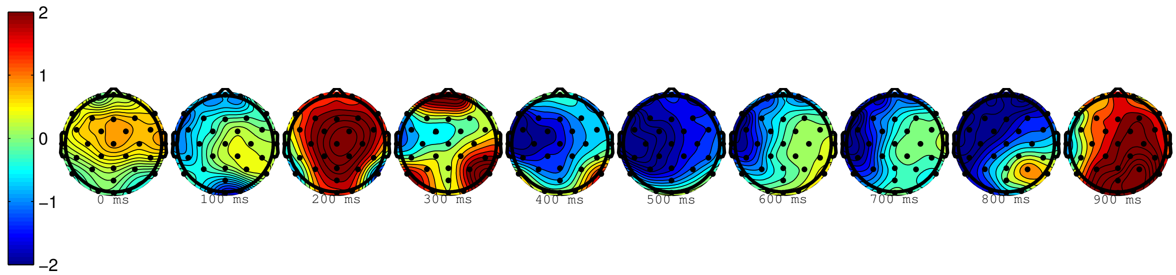
Reanalysis with subset of subjects (15), Long-distance dependency vs. Control: DO gap resolution

CONTROL	The cameraman knew *that the* former mayor would *honor* *the* soldiers before the fireworks.
WHO	The cameraman knew *who the* former mayor would honor *before* the fireworks.

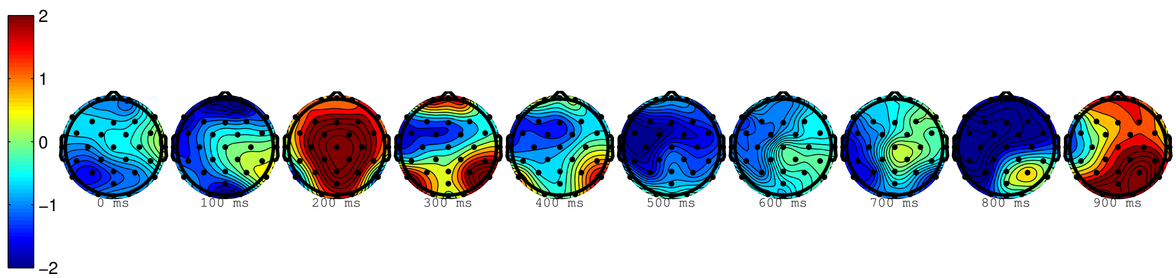
ERPs

Figure A.67: Reanalysis with subset of subjects (15), PP, Long-distance dependency vs. DO, Control: topoplots

DO, Control



PP, Long-distance dependency



Difference plots

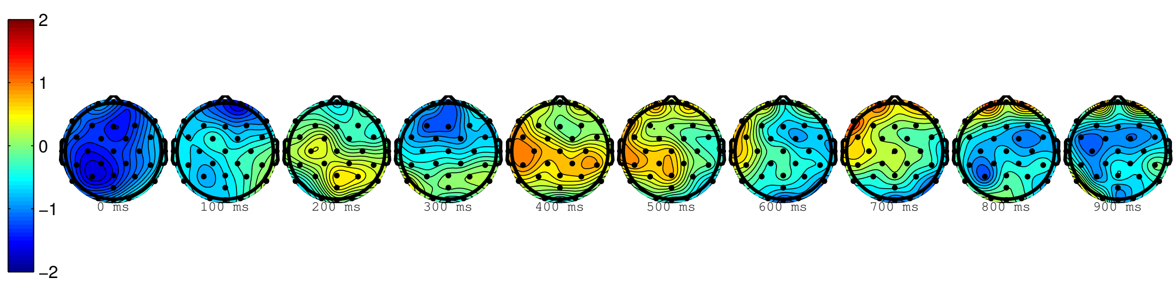


Figure A.68: Reanalysis with subset of subjects (15), PP, Long-distance dependency vs. DO, Control control: t_{max} tests

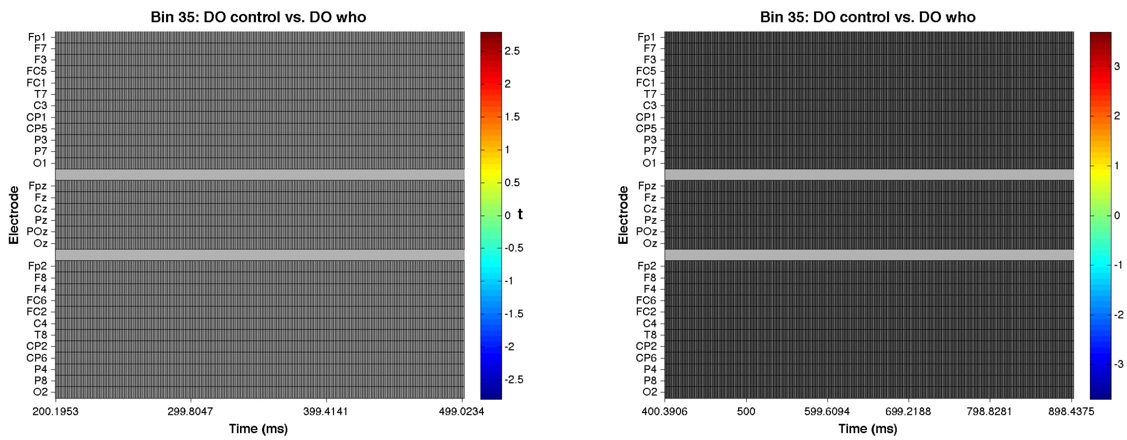
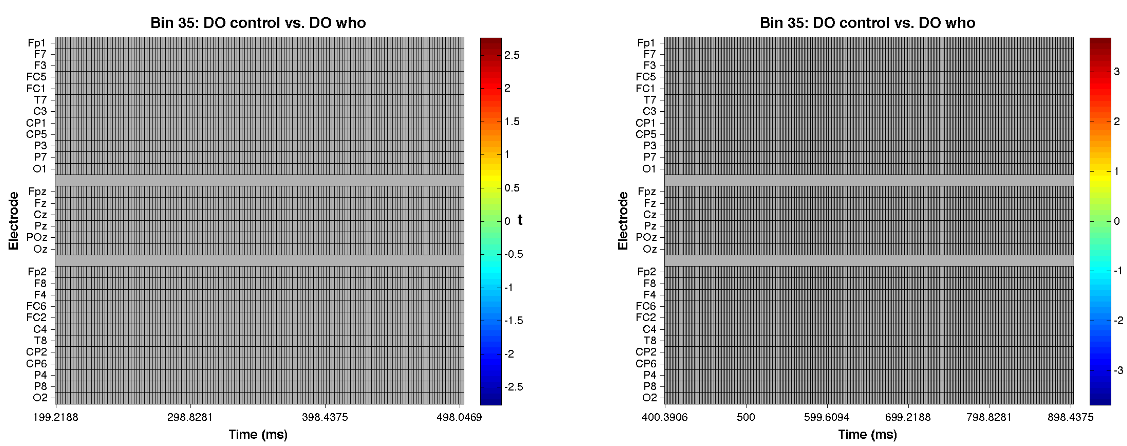


Figure A.69: Reanalysis with subset of subjects (15), PP, Long-distance dependency vs. DO, Control control: cluster mass permutation tests



TFRs

Figure A.70: Reanalysis with subset of subjects (15), PP, Long-distance dependency vs. DO, Control: TFR

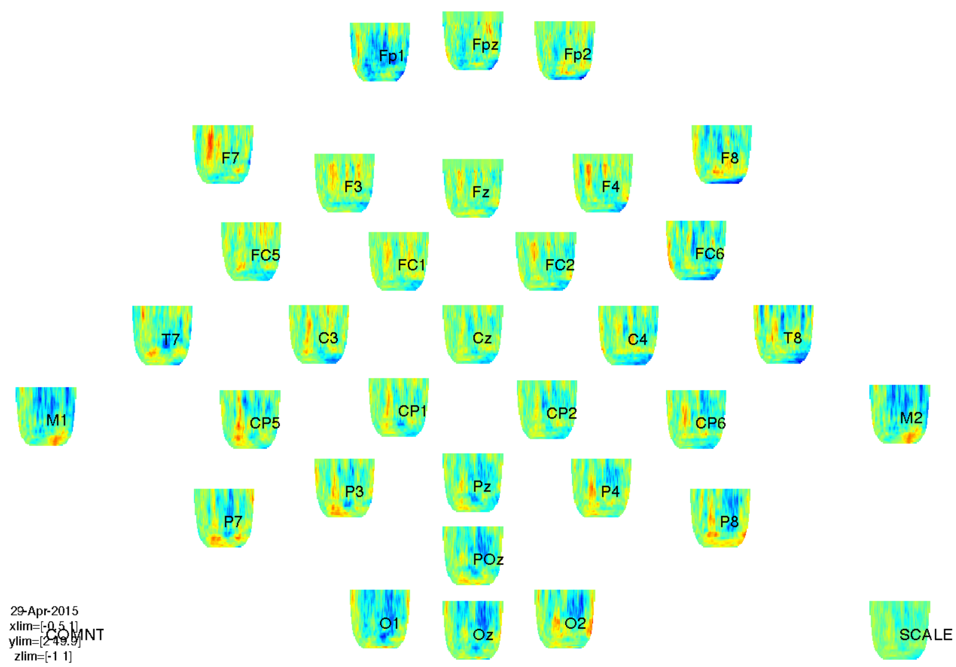


Figure A.71: Reanalysis with subset of subjects (15), PP, Long-distance dependency vs. DO, Control: Theta band (4-7Hz) masked stats TFR

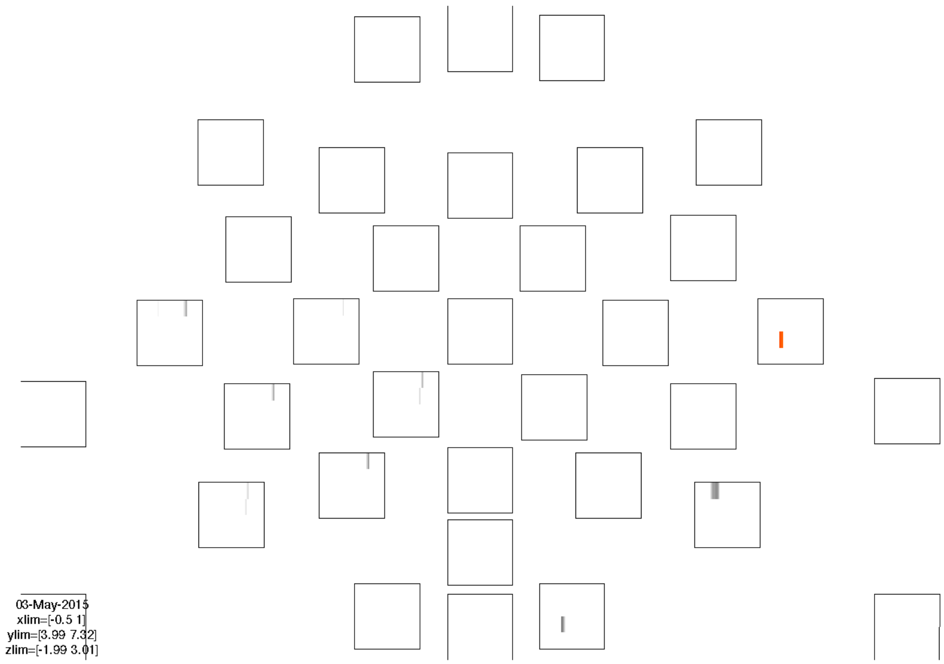


Figure A.72: Reanalysis with subset of subjects (15), PP, Long-distance dependency vs. DO, Control: Theta band (4-7Hz) masked stats TFR, significant channels

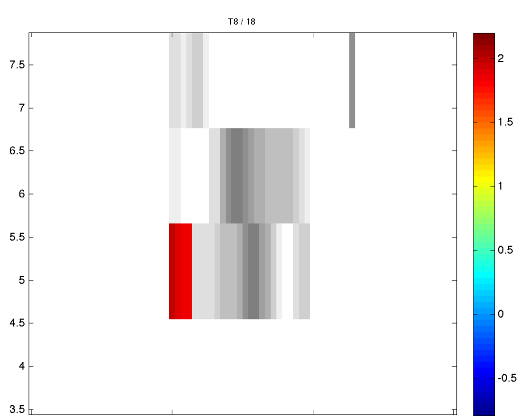


Figure A.73: Reanalysis with subset of subjects (15), PP, Long-distance dependency vs. DO, Control: Alpha band (8-12Hz) masked stats TFR

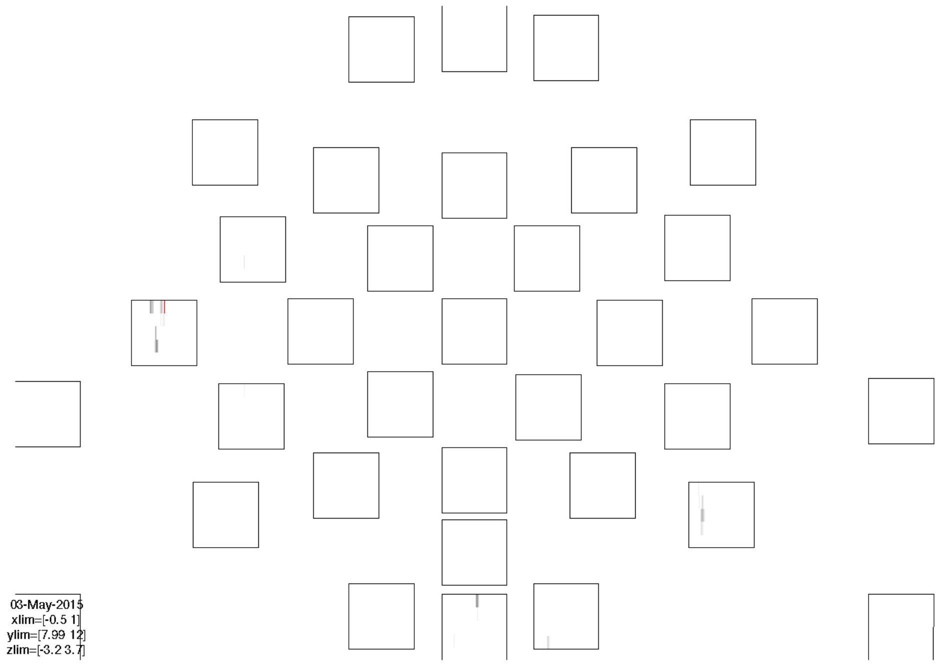


Figure A.74: Reanalysis with subset of subjects (15), PP, Long-distance dependency vs. DO, Control: Alpha band (8-12Hz) masked stats TFR, significant channels

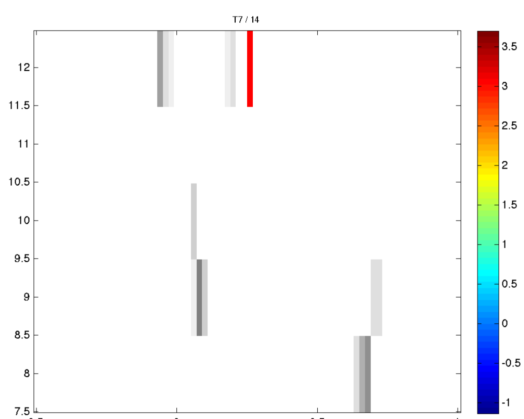


Figure A.75: Reanalysis with subset of subjects (15), PP, Long-distance dependency vs. DO, Control: Lower Beta band (13-20Hz) masked stats TFR

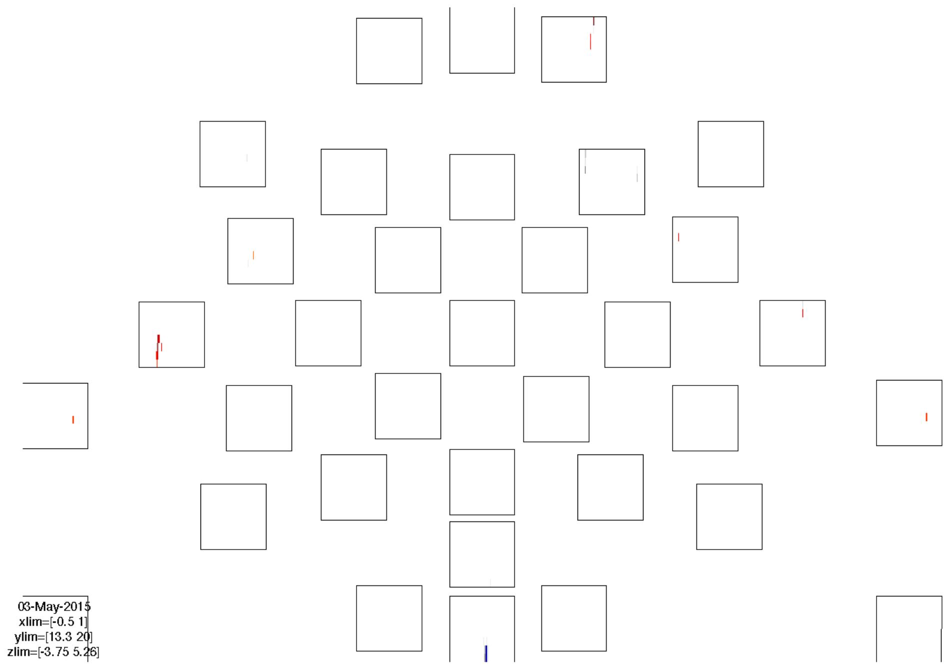


Figure A.76: Reanalysis with subset of subjects (15), PP, Long-distance dependency vs. DO, Control: Lower Beta band (13-20Hz) masked stats TFR, significant channels

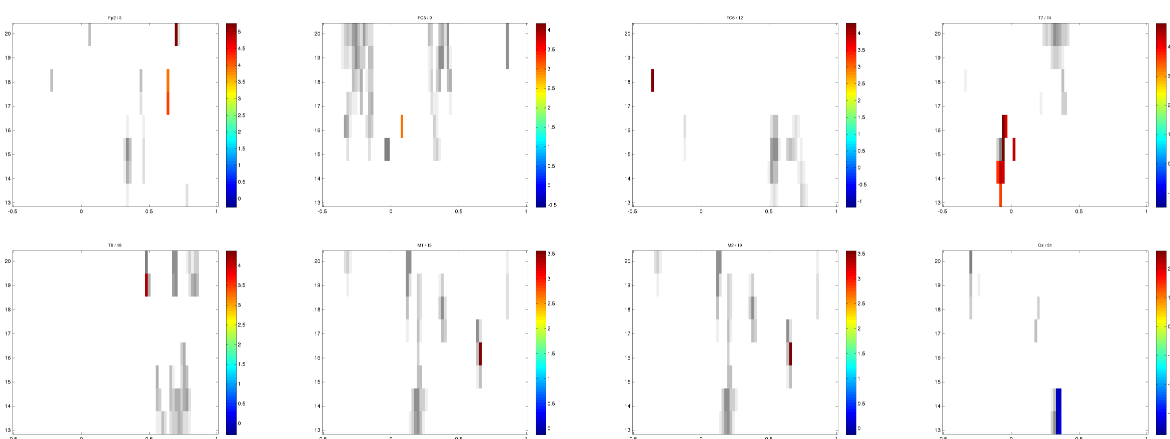


Figure A.77: Reanalysis with subset of subjects (15), PP, Long-distance dependency vs. DO, Control: Upper Beta band (21-30Hz) masked stats TFR

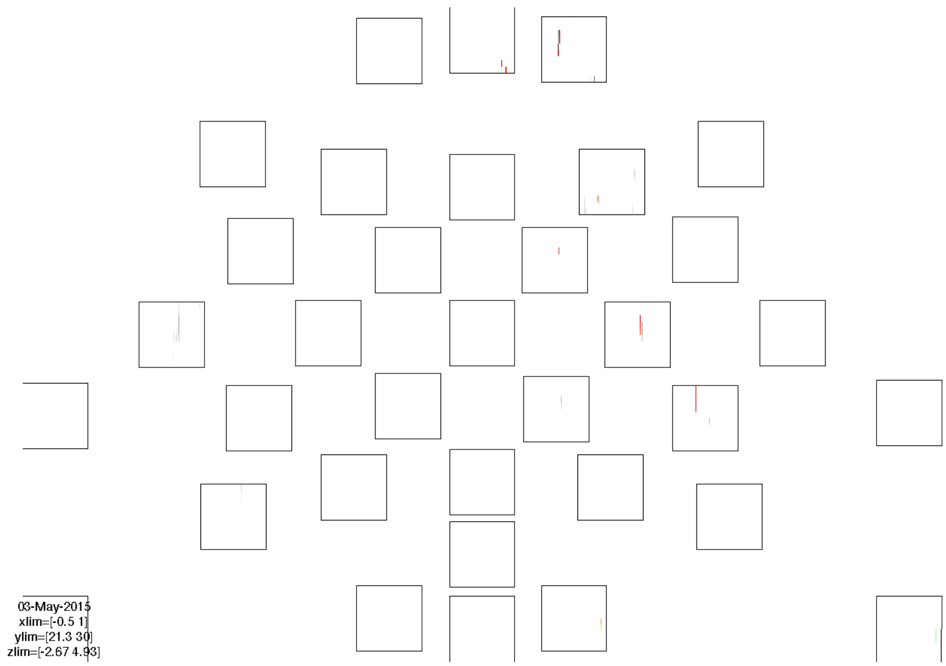


Figure A.78: Reanalysis with subset of subjects (15), PP, Long-distance dependency vs. DO, Control: Upper Beta band (21-30Hz) masked stats TFR, significant channels

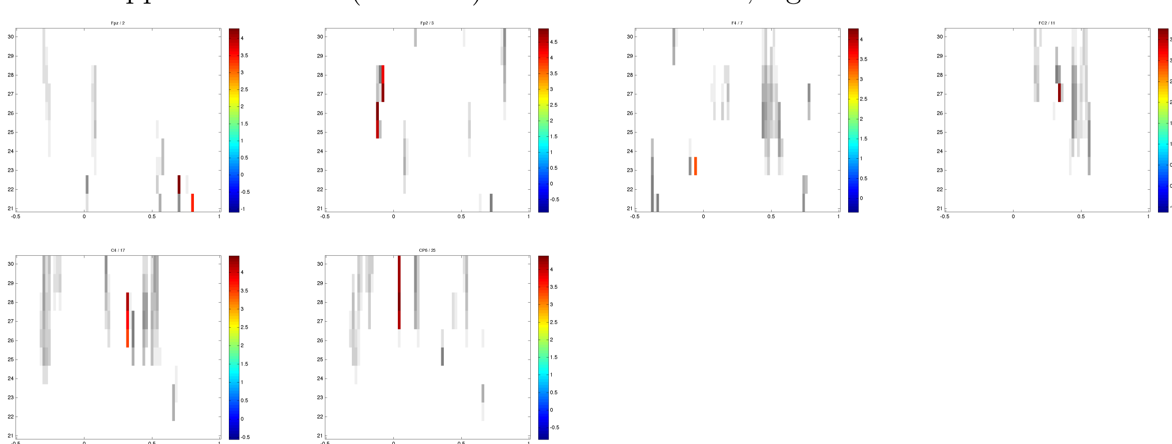


Figure A.79: Reanalysis with subset of subjects (15), PP, Long-distance dependency vs. DO, Control: Gamma band (31-40Hz) masked stats TFR

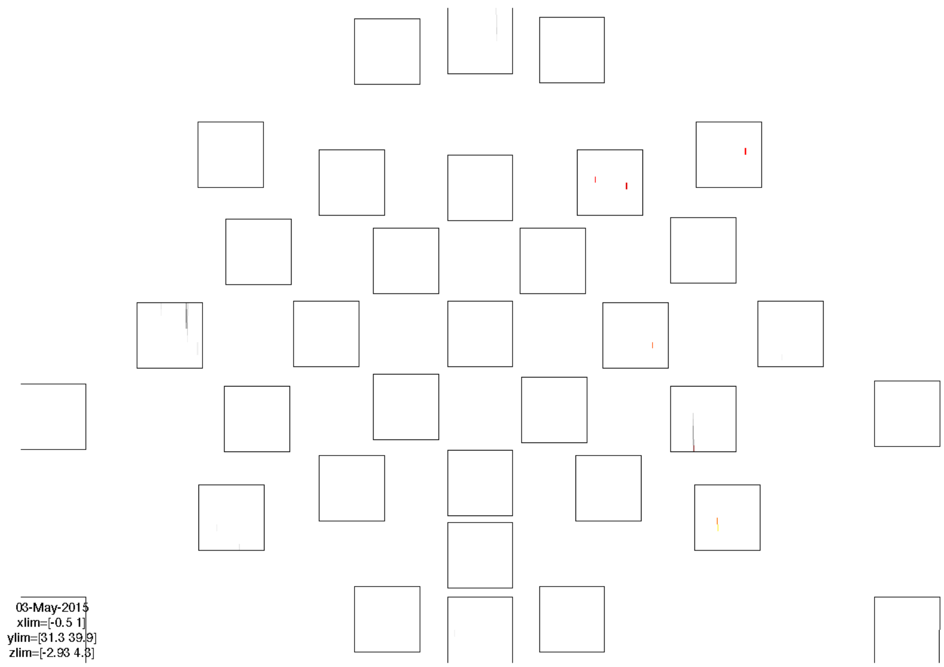


Figure A.80: Reanalysis with subset of subjects (15), PP, Long-distance dependency vs. DO, Control: Gamma band (31-40Hz) masked stats TFR, significant channels

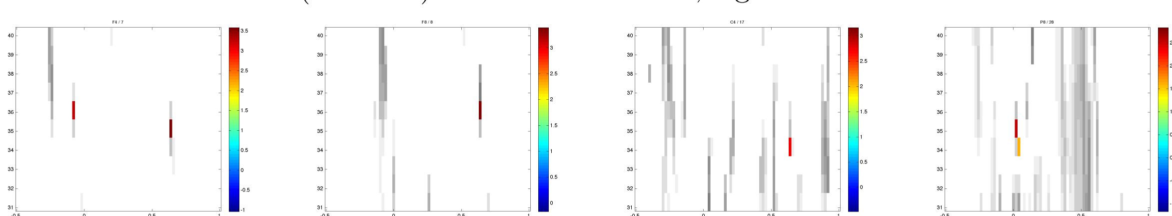
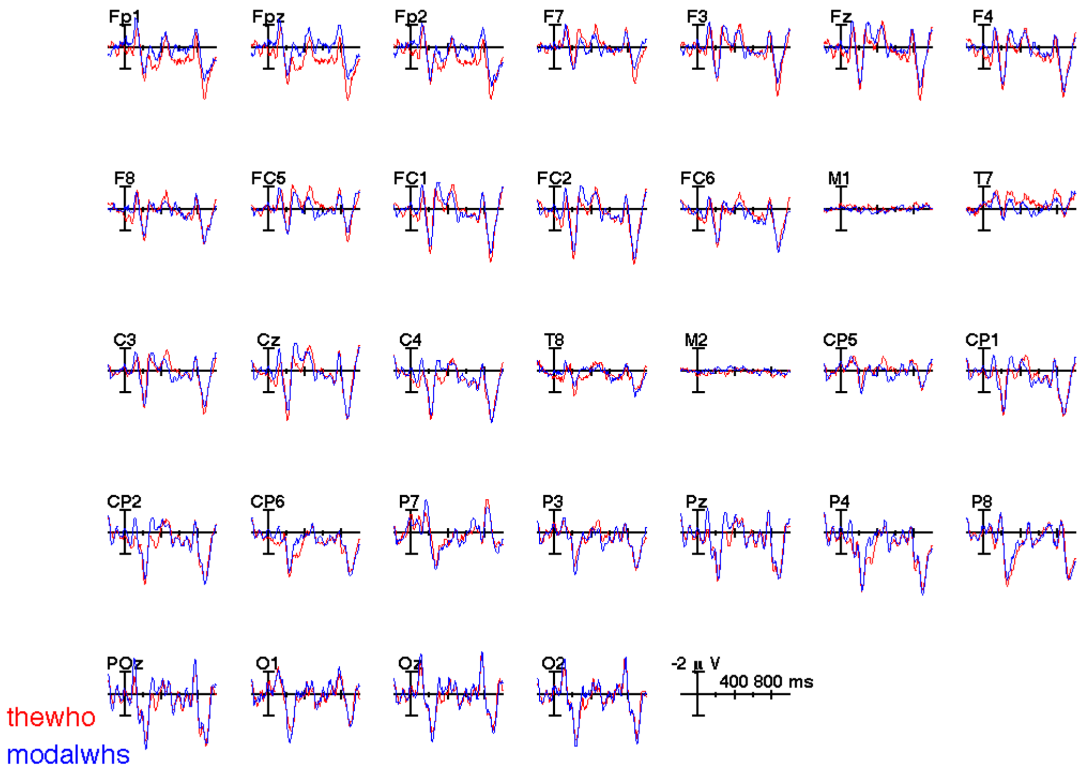


Figure A.81: Reanalysis with subset of subjects (15), *the*, Long-distance dependency vs. Modal, Short-distance dependency: ERPs



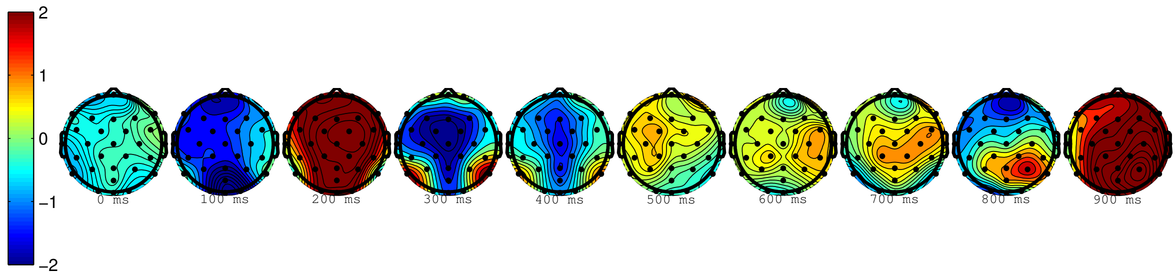
Reanalysis with subset of subjects (15), Long-distance dependency vs. Short-distance dependency: first word of dependency vs. gap resolution

WHS	The cameraman knew *who* *would* honor the soldiers before *the* fireworks.
WHO	The cameraman knew *who* *the* former mayor would honor *before* the fireworks.

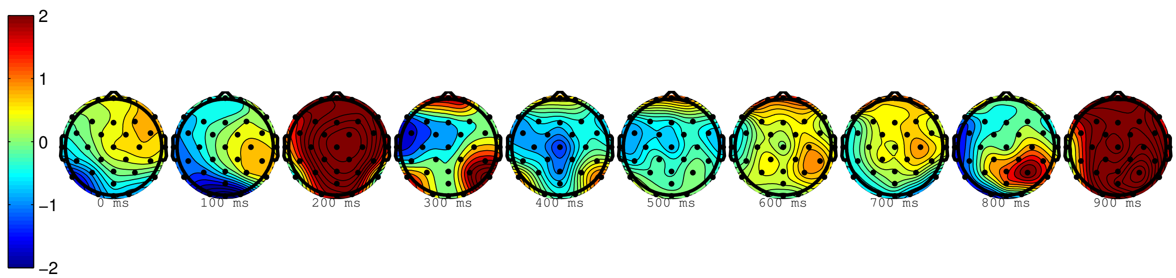
ERPs

Figure A.82: Reanalysis with subset of subjects (15), *the*, Long-distance vs. Modal, Short-distance dependency: topoplots

Modal, Short-distance dependency



the, Long-distance dependency



Difference plots

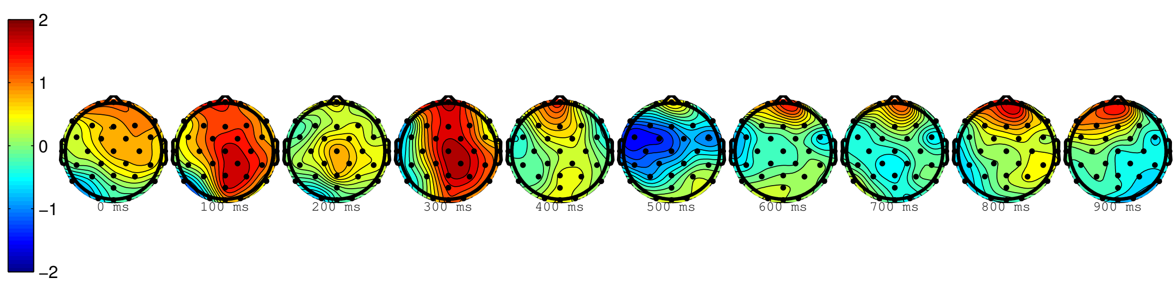


Figure A.83: Reanalysis with subset of subjects (15), *the*, Long-distance vs. Modal, Short-distance dependency: t_{max} tests

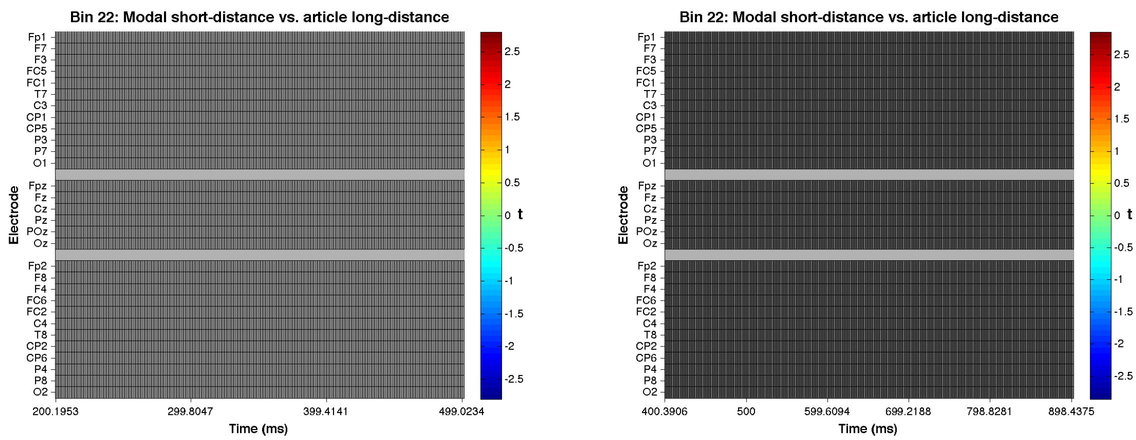
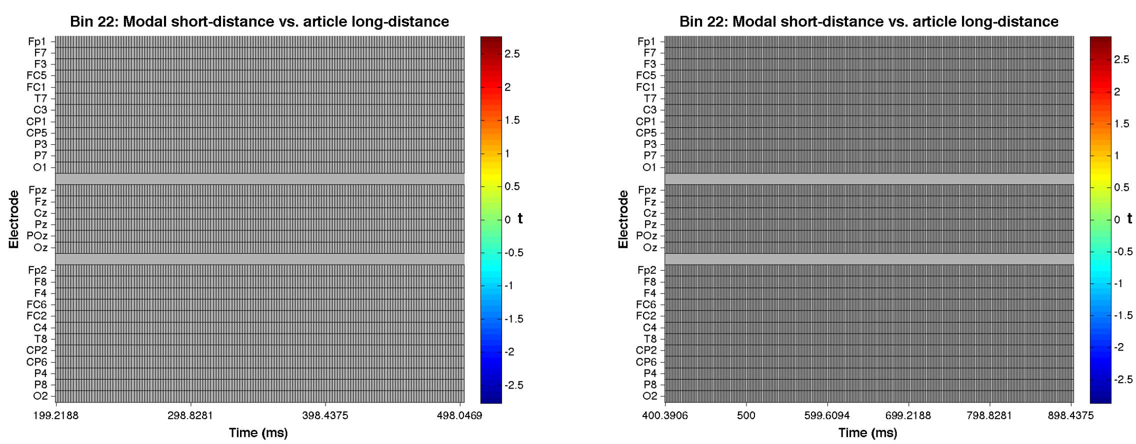


Figure A.84: Reanalysis with subset of subjects (15), *the*, Long-distance vs. Modal, Short-distance dependency: cluster mass permutation tests



TFRs

Figure A.85: Reanalysis with subset of subjects (15), First word of Long-distance dependency vs. gap resolution in Short-distance dependency: TFR

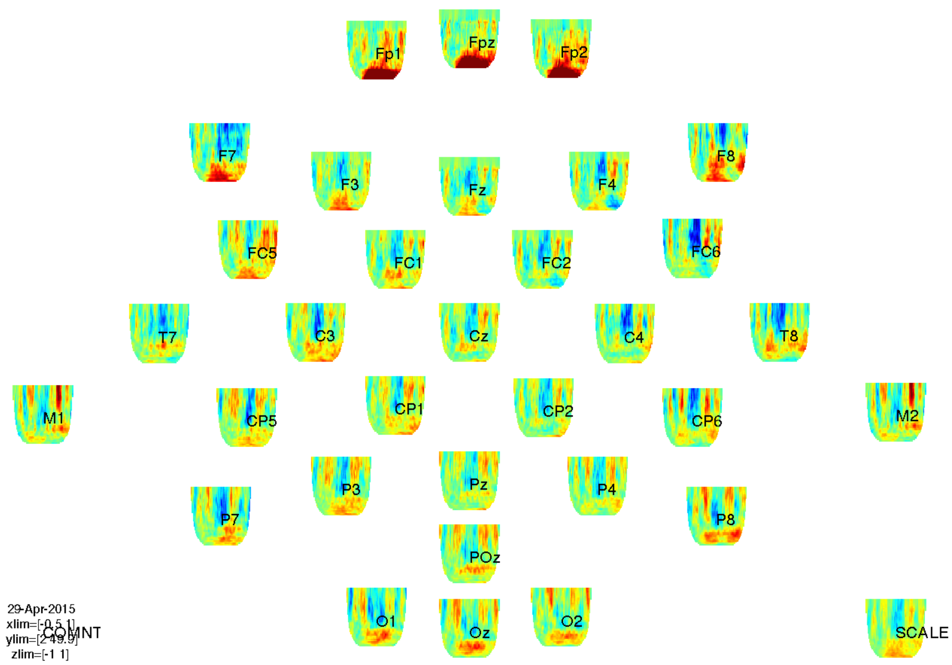


Figure A.86: Reanalysis with subset of subjects (15), First word of Long-distance dependency vs. gap resolution in Short-distance dependency: Alpha band (8-12Hz) masked stats TFR

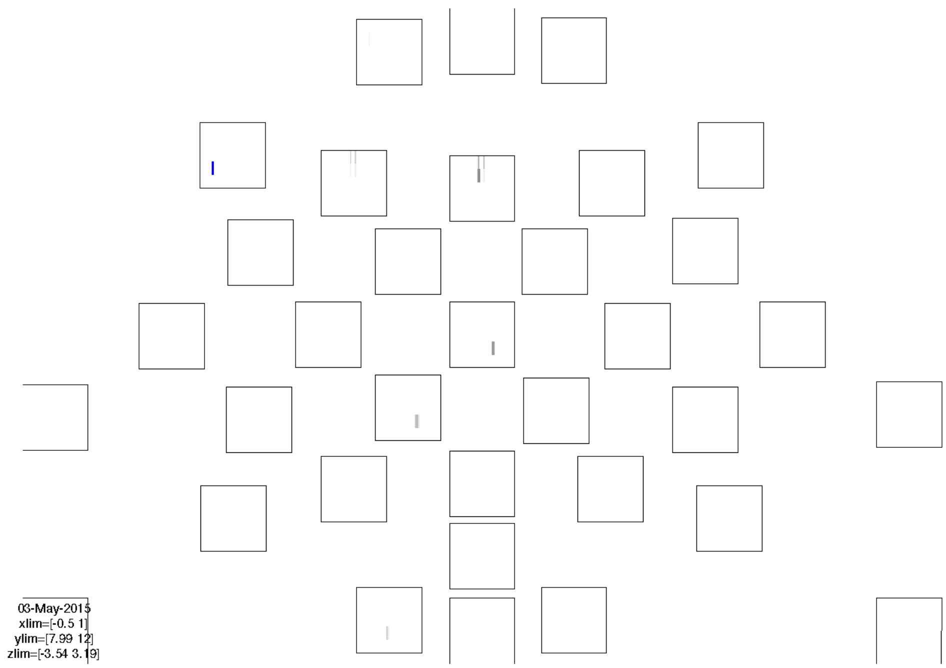


Figure A.87: Reanalysis with subset of subjects (15), First word of Long-distance dependency vs. gap resolution in Short-distance dependency: Alpha band (8-12Hz) masked stats TFR, significant channels

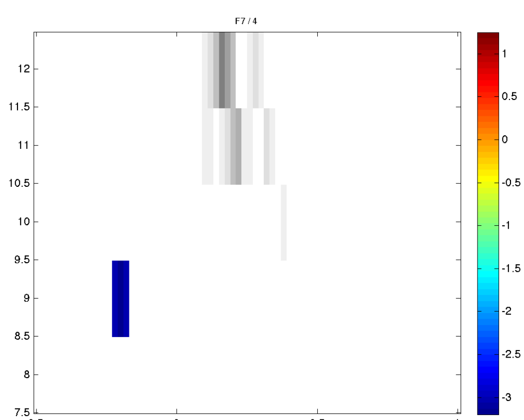


Figure A.88: Reanalysis with subset of subjects (15), First word of Long-distance dependency vs. gap resolution in Short-distance dependency: Lower Beta band (13-20Hz) masked stats TFR

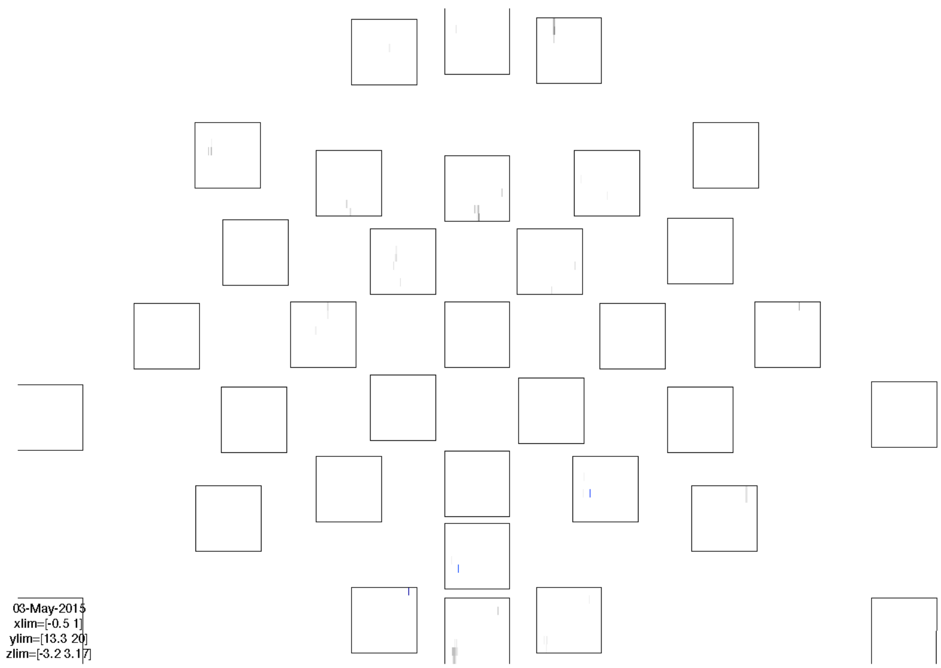


Figure A.89: Reanalysis with subset of subjects (15), First word of Long-distance dependency vs. gap resolution in Short-distance dependency: Lower Beta band (13-20Hz) masked stats TFR, significant channels

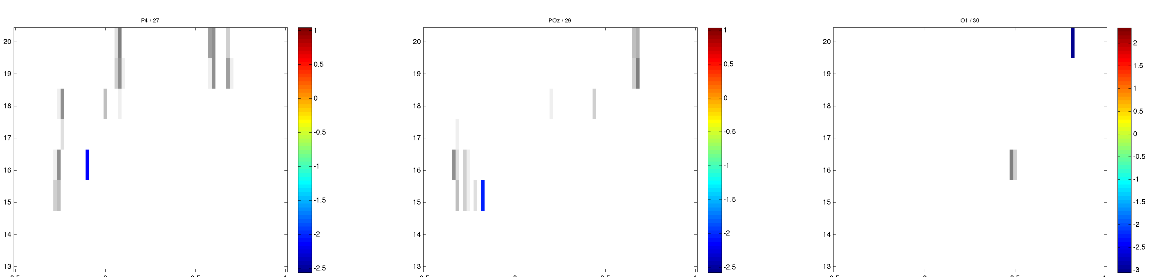
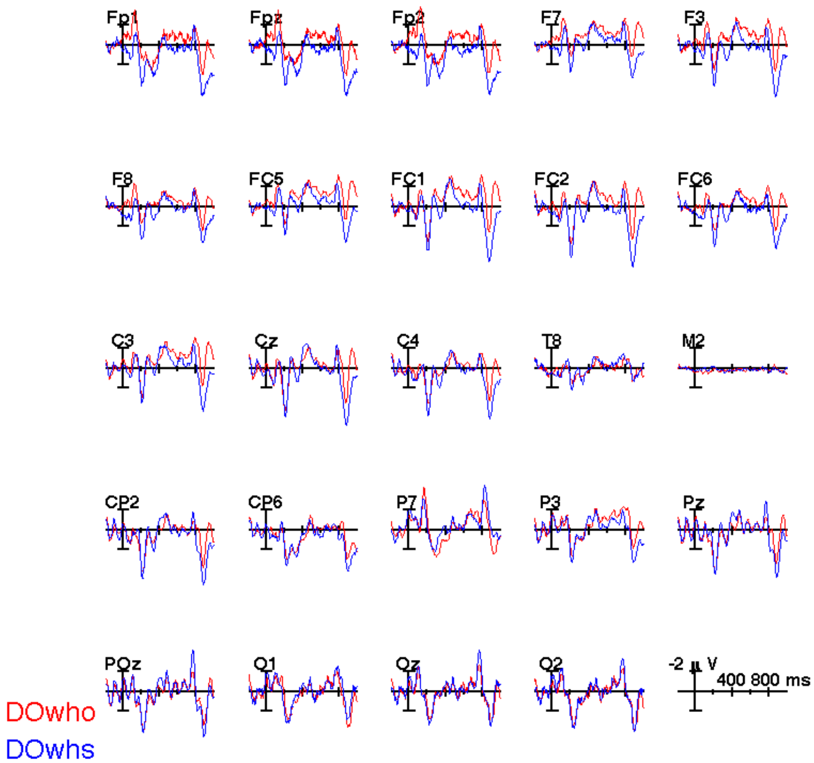


Figure A.90: Reanalysis with subset of subjects (15), PP, Long-distance dependency vs. DO, Short-distance dependency: ERPs



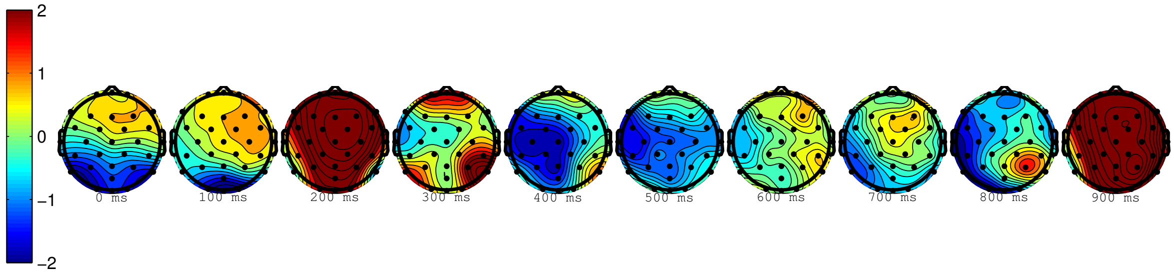
Reanalysis with subset of subjects (15), Long-distance dependency vs. Short-distance dependency: gap resolution vs. DO

WHO The cameraman knew *who* *the* former mayor would honor *before* the fireworks.
WHS The cameraman knew *who* *would* honor the soldiers before *the* fireworks.

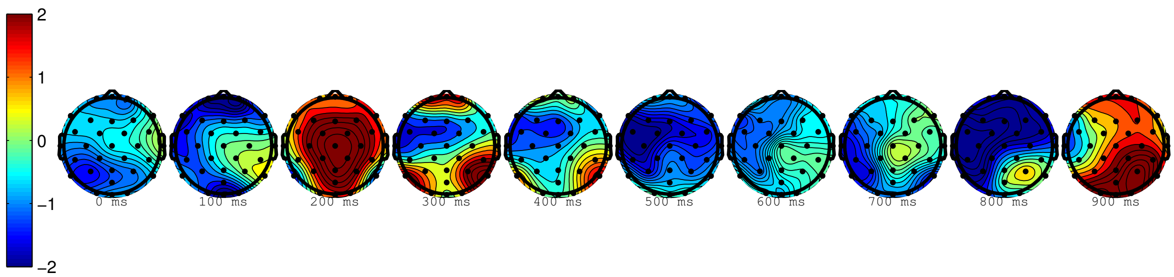
ERPs

Figure A.91: Reanalysis with subset of subjects (15), PP, Long-distance vs. DO, Short-distance dependency: topoplots

DO, Short-distance dependency



PP, Long-distance dependency



Difference plots

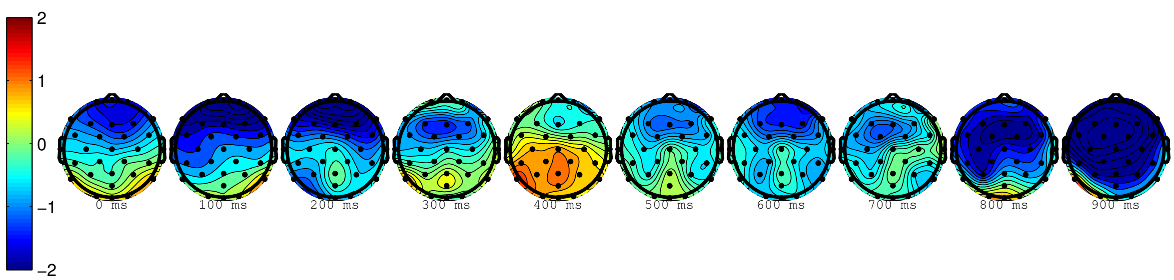


Figure A.92: Reanalysis with subset of subjects (15), PP, Long-distance vs. DO, Short-distance dependency: t_{max} tests

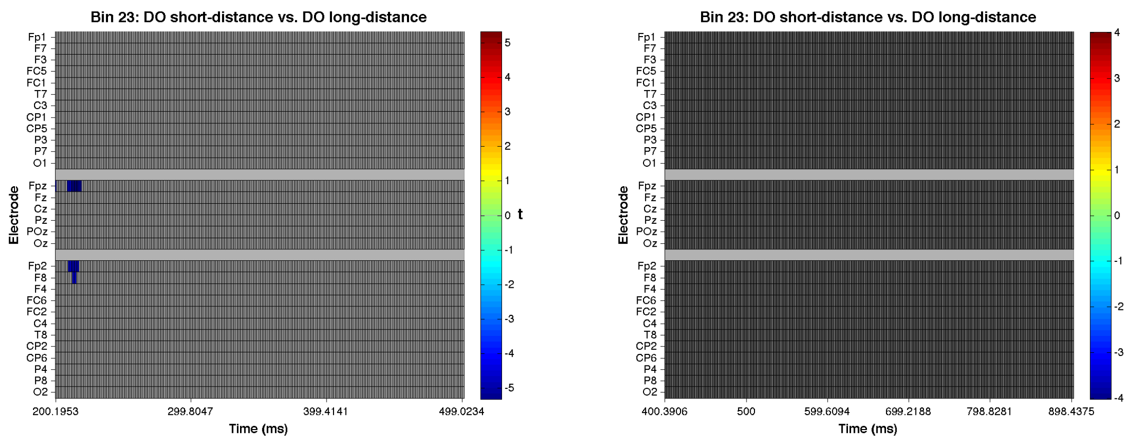
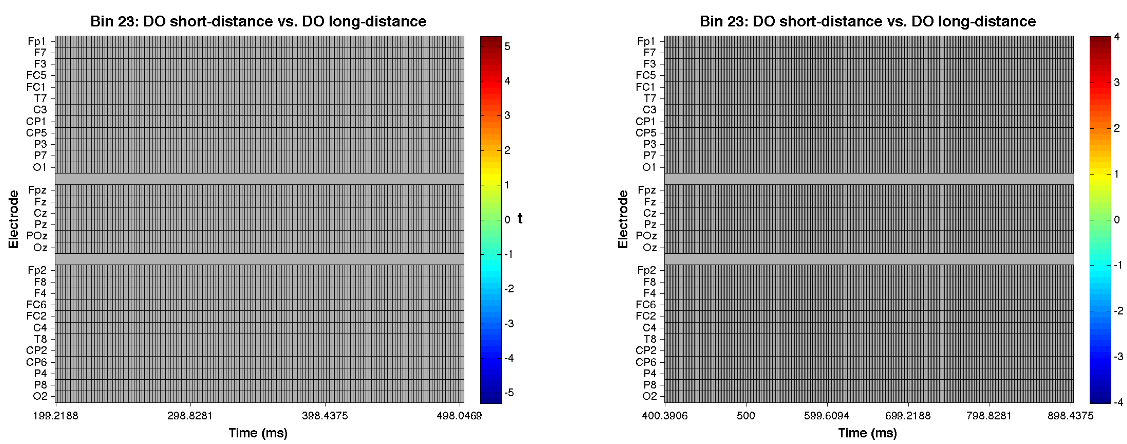


Figure A.93: Reanalysis with subset of subjects (15), PP, Long-distance vs. DO, Short-distance dependency: cluster mass permutation tests



TFRs

Figure A.94: Reanalysis with subset of subjects (15), Gap resolution in Long-distance dependency vs. DO of Short-distance dependency: TFR

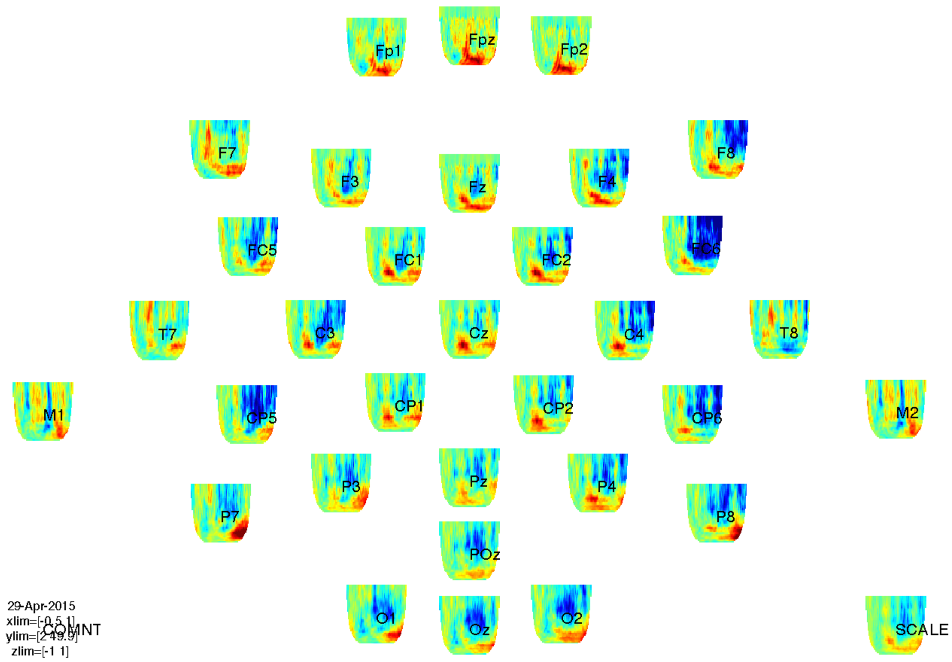


Figure A.95: Reanalysis with subset of subjects (15), Gap resolution in Long-distance dependency vs. DO of Short-distance dependency: Theta band (4-7Hz) masked stats TFR

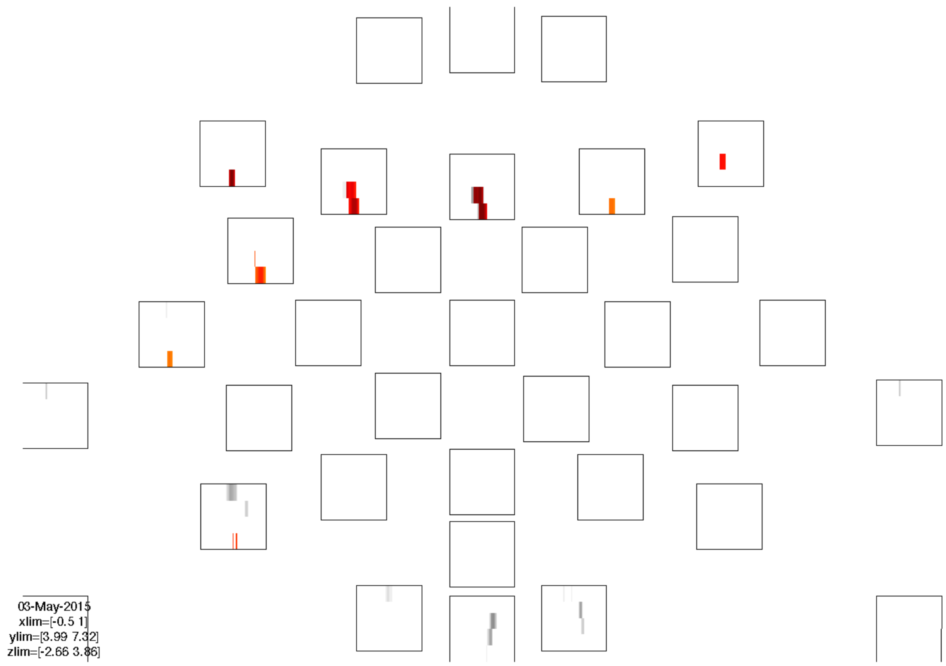


Figure A.96: Reanalysis with subset of subjects (15), Gap resolution in Long-distance dependency vs. DO of Short-distance dependency: Theta band (4-7Hz) masked stats TFR, significant channels

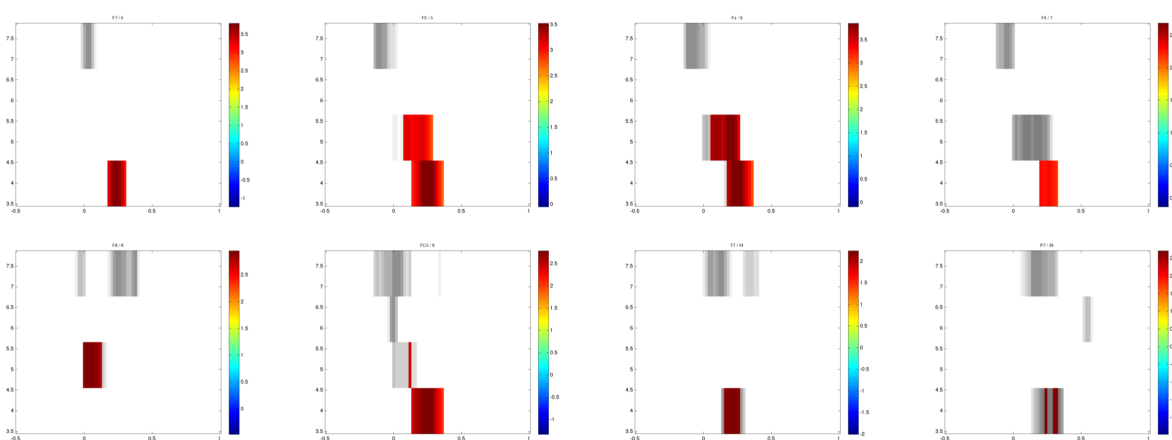


Figure A.97: Reanalysis with subset of subjects (15), Gap resolution in Long-distance dependency vs. DO of Short-distance dependency: Alpha band (8-12Hz) masked stats TFR

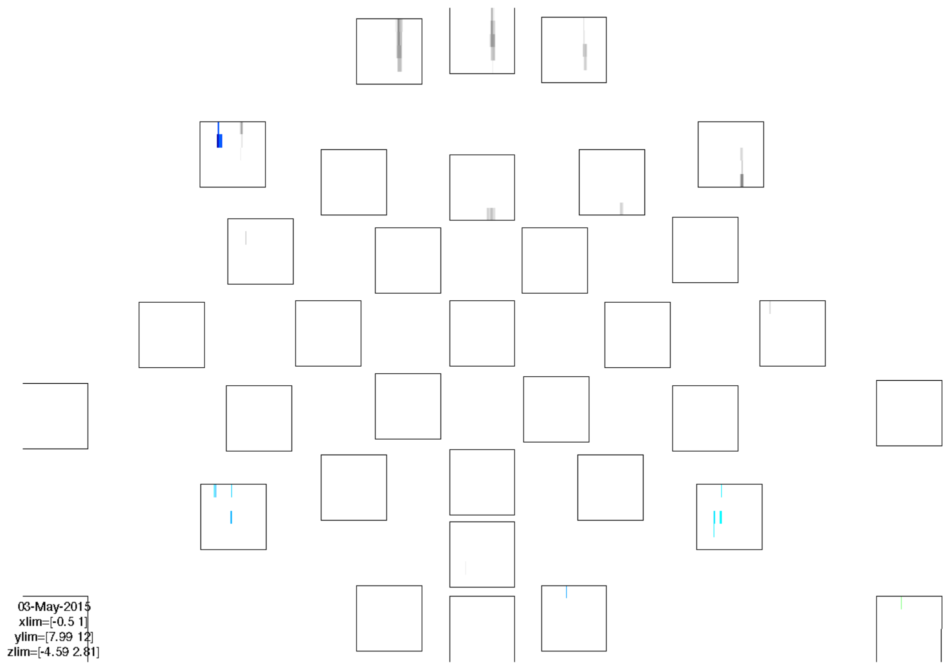


Figure A.98: Reanalysis with subset of subjects (15), Gap resolution in Long-distance dependency vs. DO of Short-distance dependency: Alpha band (8-12Hz) masked stats TFR, significant channels

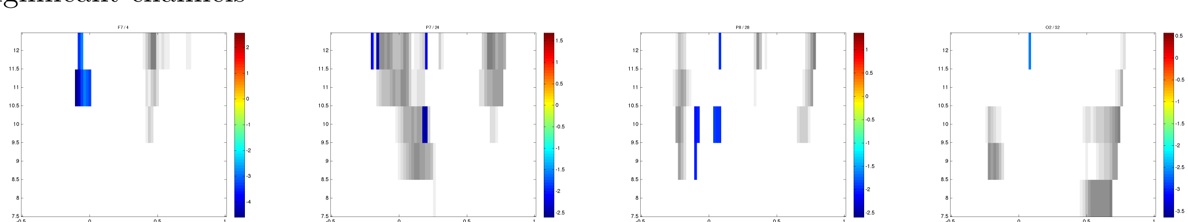


Figure A.99: Reanalysis with subset of subjects (15), Gap resolution in Long-distance dependency vs. DO of Short-distance dependency: Lower Beta band (13-20Hz) masked stats TFR

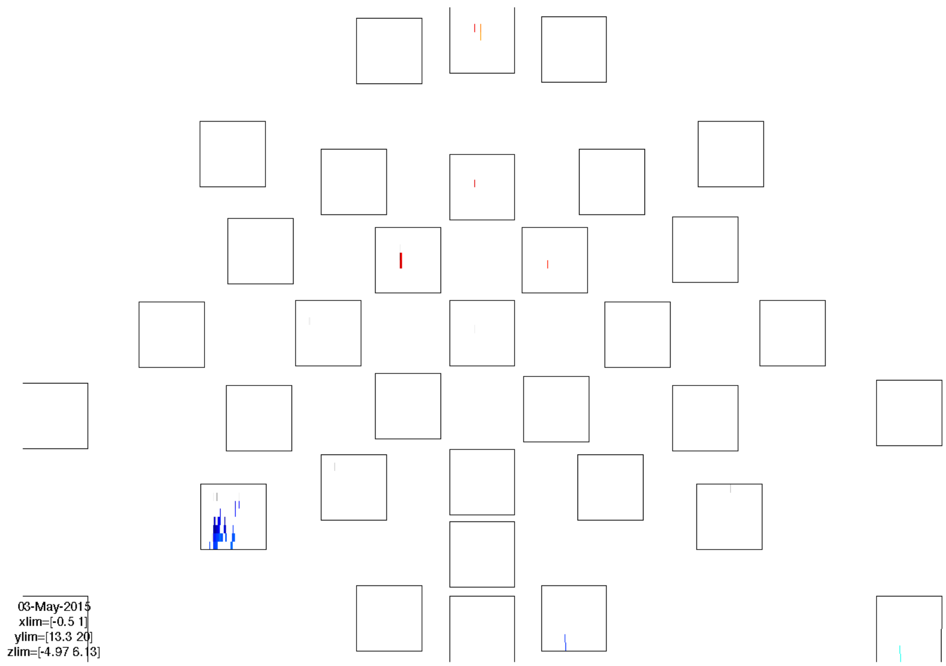


Figure A.100: Reanalysis with subset of subjects (15), Gap resolution in Long-distance dependency vs. DO of Short-distance dependency: Lower Beta band (13-20Hz) masked stats TFR, significant channels

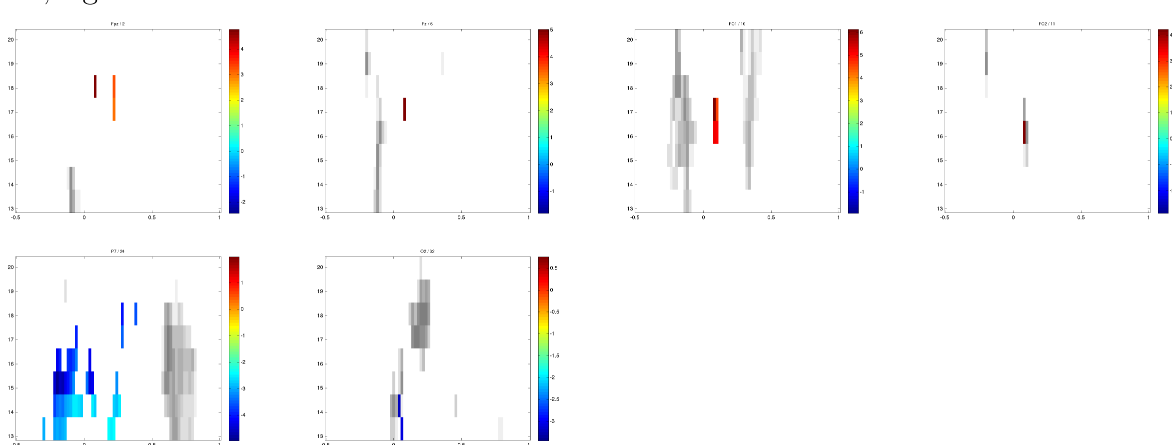


Figure A.101: Reanalysis with subset of subjects (15), Gap resolution in Long-distance dependency vs. DO of Short-distance dependency: Upper Beta band (21-30Hz) masked stats TFR

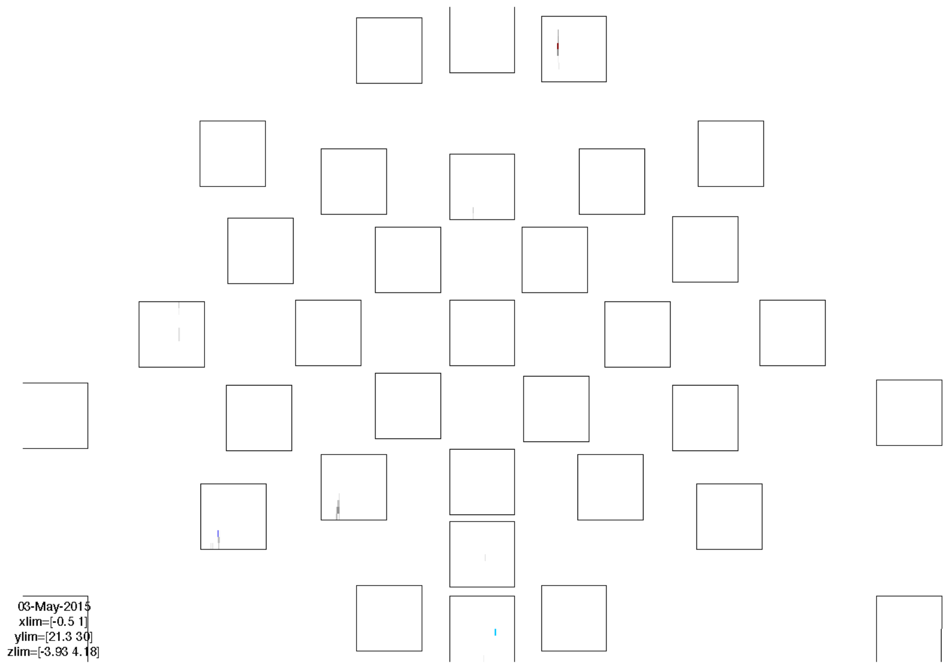


Figure A.102: Reanalysis with subset of subjects (15), Gap resolution in Long-distance dependency vs. DO of Short-distance dependency: Upper Beta band (21-30Hz) masked stats TFR, significant channels

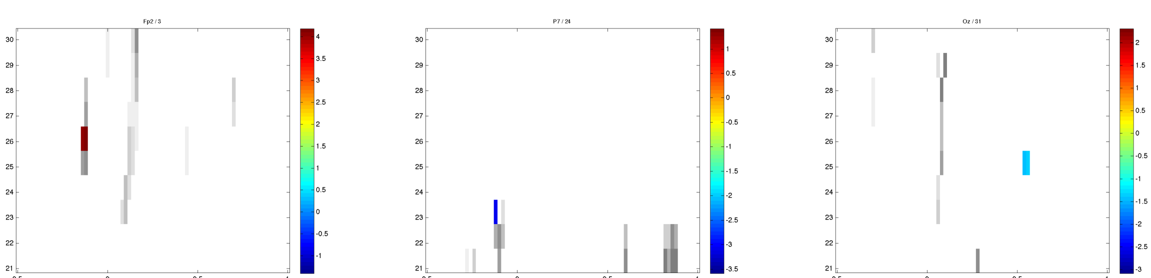
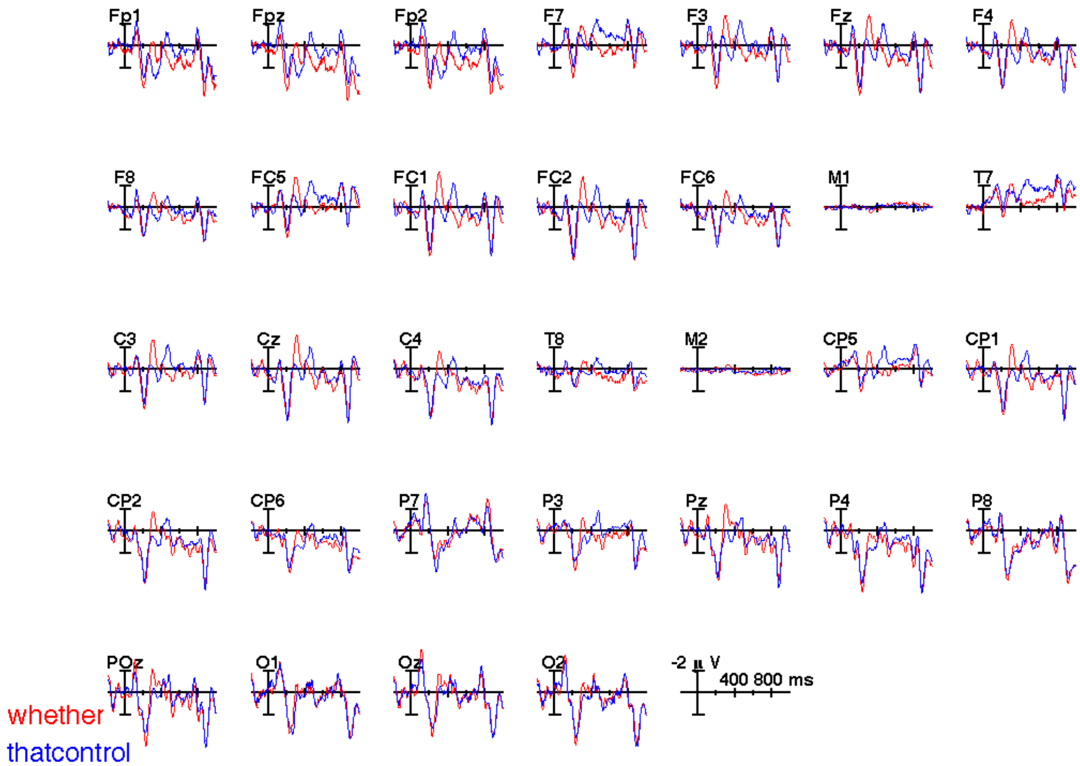


Figure A.103: Reanalysis with subset of subjects (15), Whether vs. *that*, Control: ERPs



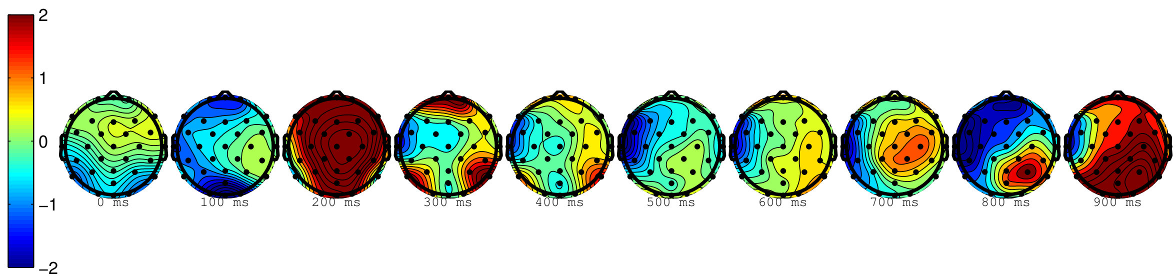
Reanalysis with subset of subjects (15): Whether complementizer vs. Control

CONTROL	The cameraman knew *that* *the* former mayor would *honor* *the* soldiers before the fireworks.
WHETHER	The cameraman knew *whether* *the* former mayor would honor *the* soldiers before the fireworks.

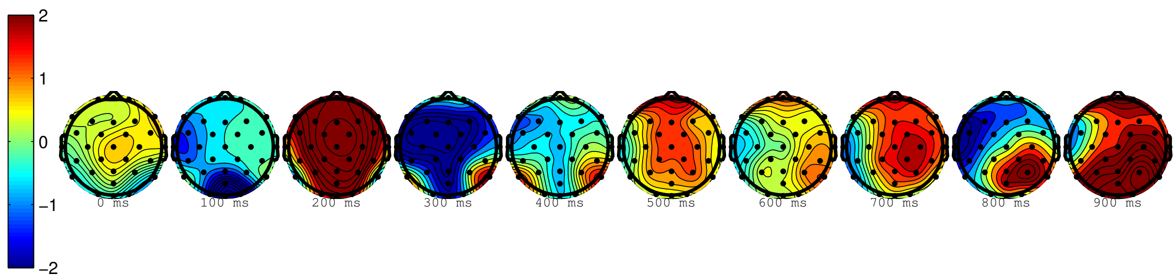
ERPs

Figure A.104: Reanalysis with subset of subjects (15), Whether vs. *that*, Control: topoplots

that Control



Whether



Difference plots

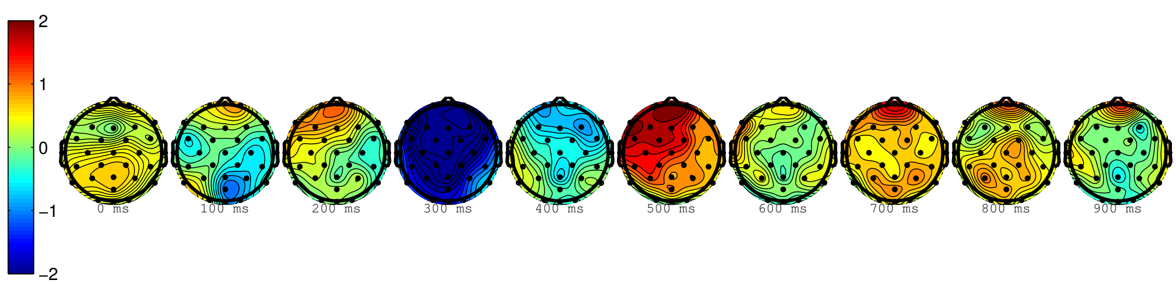


Figure A.105: Reanalysis with subset of subjects (15), Whether vs. *that*, Control: t_{max} permutation tests

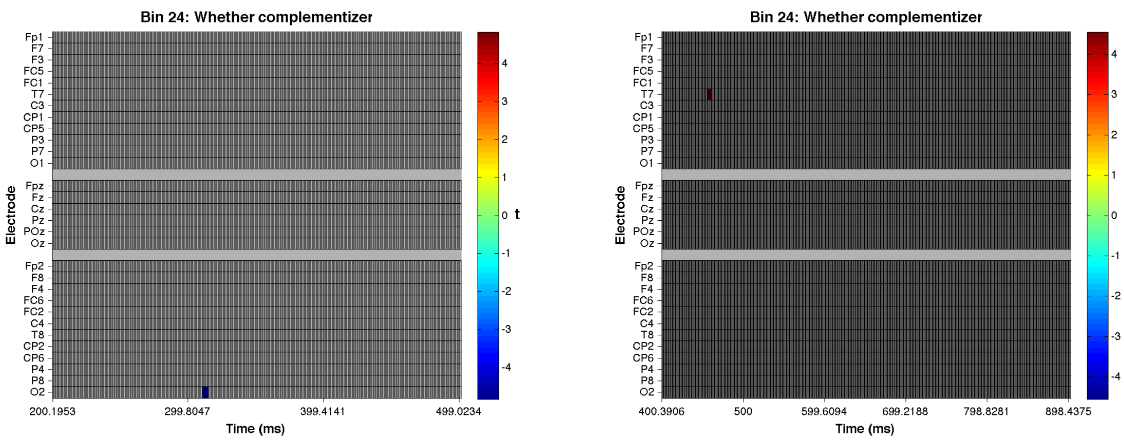
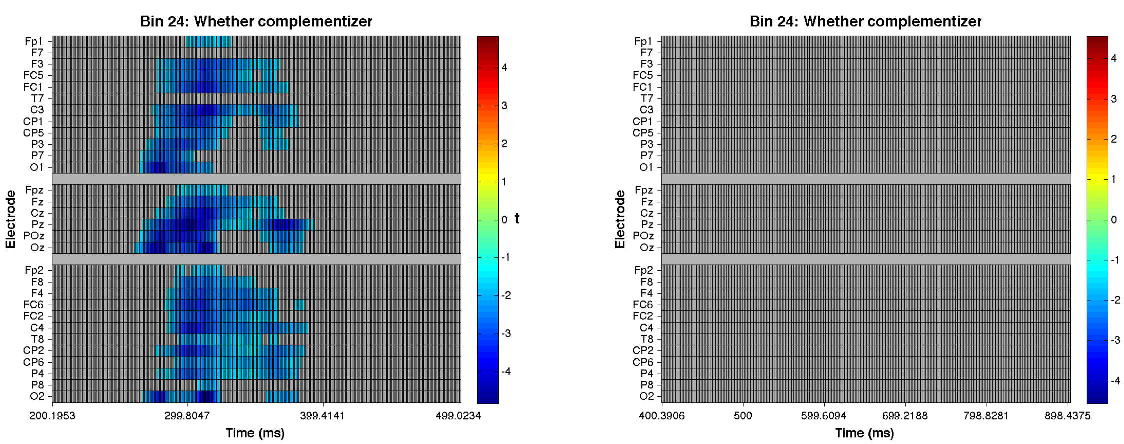


Figure A.106: Reanalysis with subset of subjects (15), Whether vs. *that*, Control: cluster mass permutation tests



TFRs

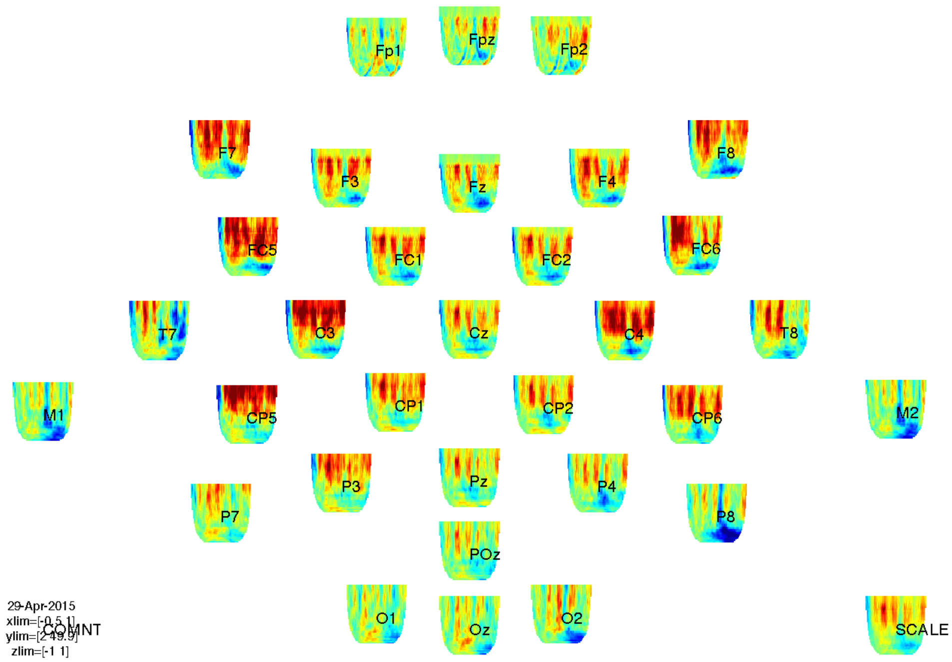


Figure A.107: Reanalysis with subset of subjects (15), Whether complementizer vs. that: TFR

Figure A.108: Reanalysis with subset of subjects (15), Whether complementizer vs. that: Alpha band (8-12Hz) masked stats TFR

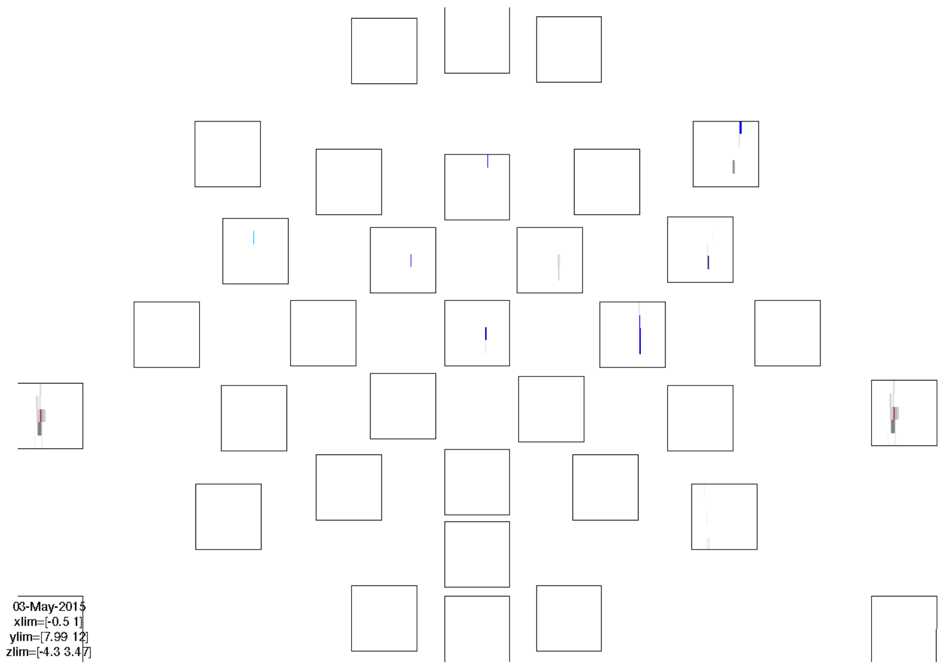
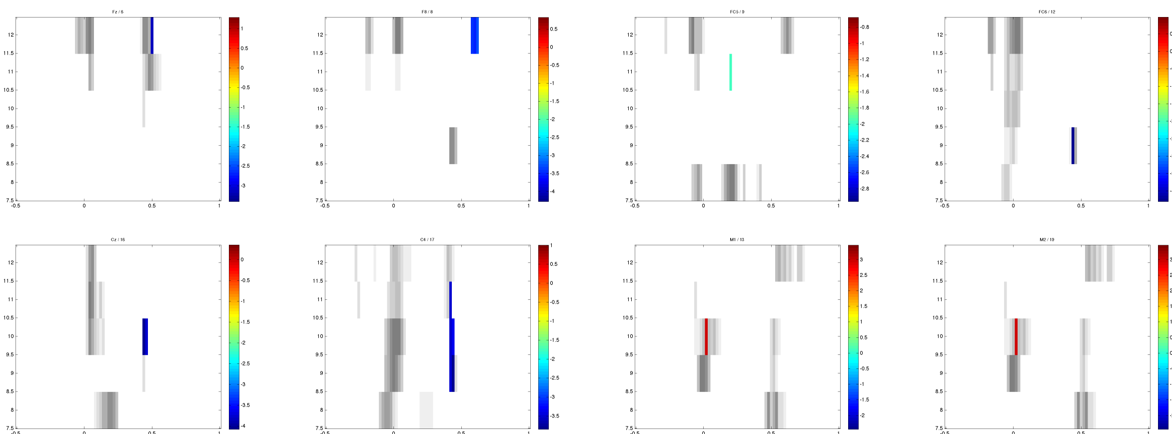


Figure A.109: Reanalysis with subset of subjects (15), Whether complementizer vs. that: Alpha band (8-12Hz) masked stats TFR, significant channels



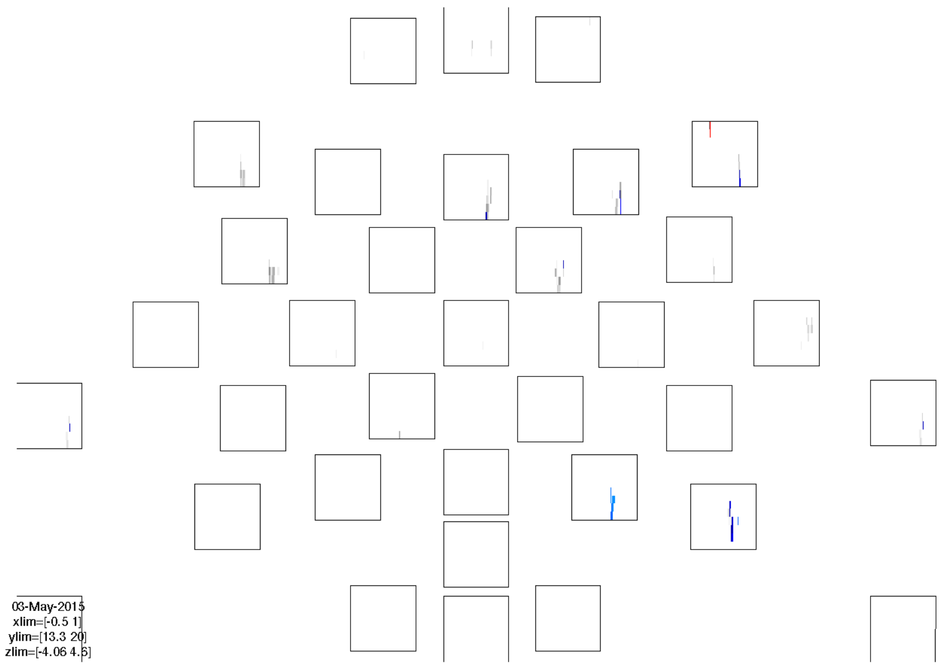


Figure A.110: Reanalysis with subset of subjects (15), Whether complementizer vs. that: Lower Beta band (13-20Hz) masked stats TFR

Figure A.111: Reanalysis with subset of subjects (15), Whether complementizer vs. that: Lower Beta band (13-20Hz) masked stats TFR, significant channels

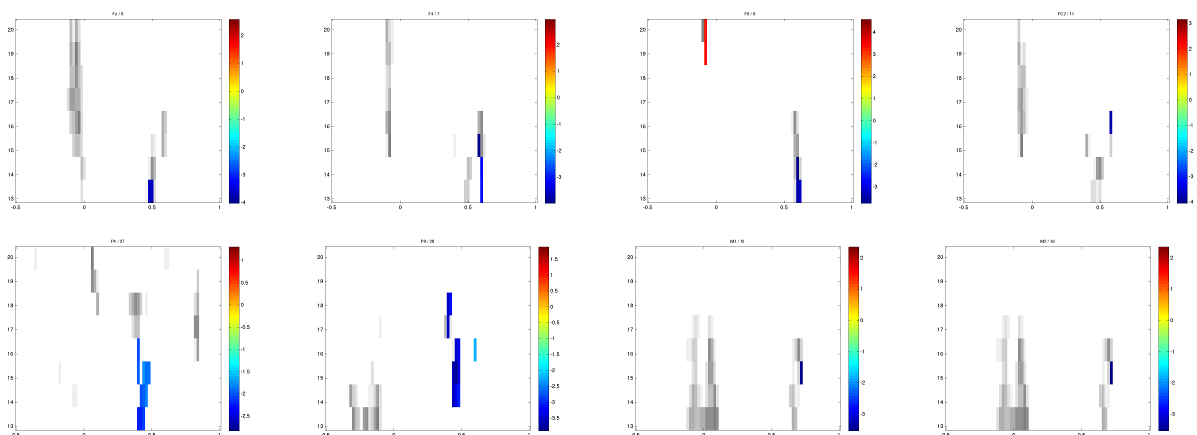


Figure A.112: Reanalysis with subset of subjects (15), Whether complementizer vs. that: Gamma band (31-40Hz) masked stats TFR

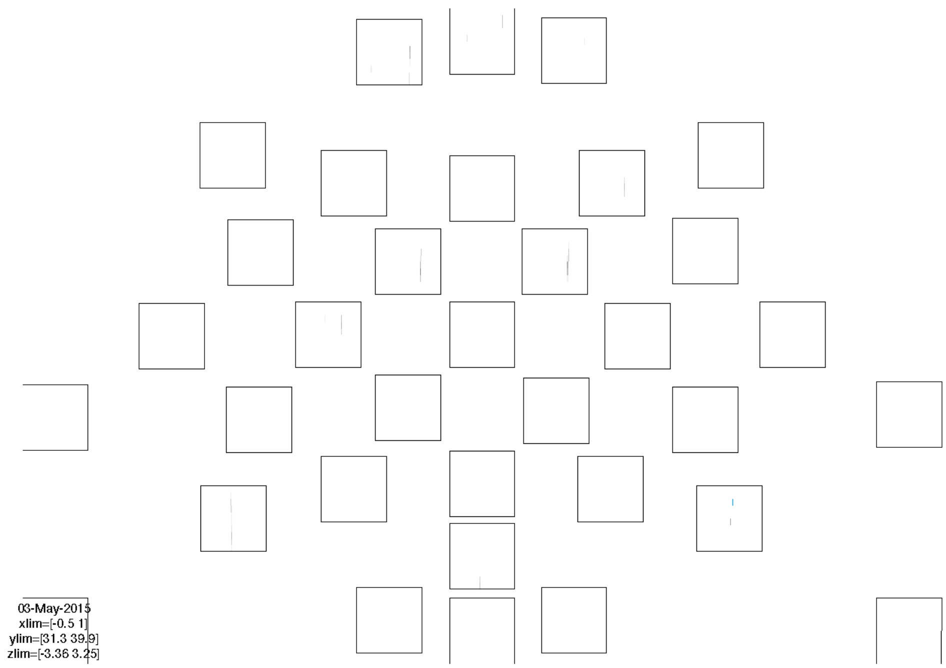


Figure A.113: Reanalysis with subset of subjects (15), Whether complementizer vs. that: Gamma band (31-40Hz) masked stats TFR, significant channels

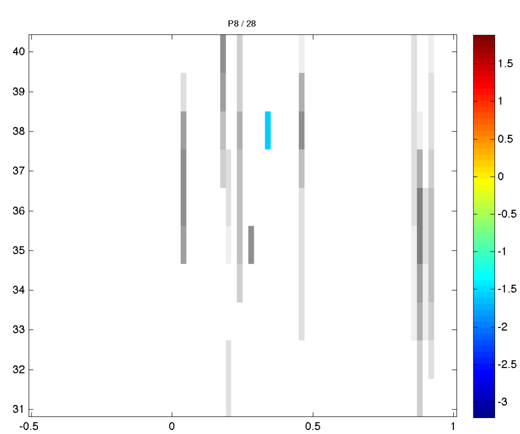
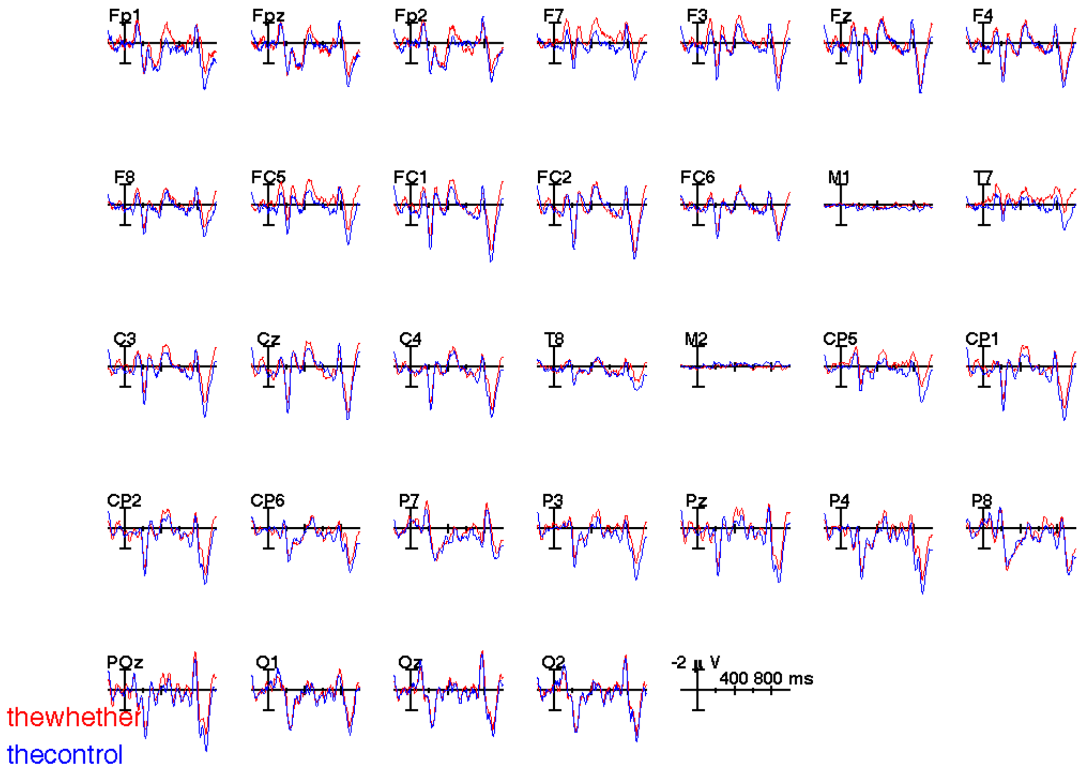


Figure A.114: Reanalysis with subset of subjects (15), *the*, Whether vs. *the*, Control: ERPs



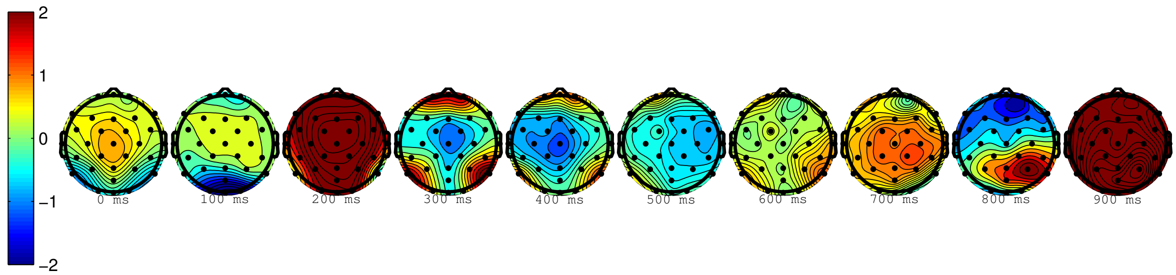
Reanalysis with subset of subjects (15), First word after *whether* complementizer vs. first word after control complementizer *that*

CONTROL	The cameraman knew *that* *the* former mayor would *honor* *the* soldiers before the fireworks.
WHETHER	The cameraman knew *whether* *the* former mayor would honor *the* soldiers before the fireworks.

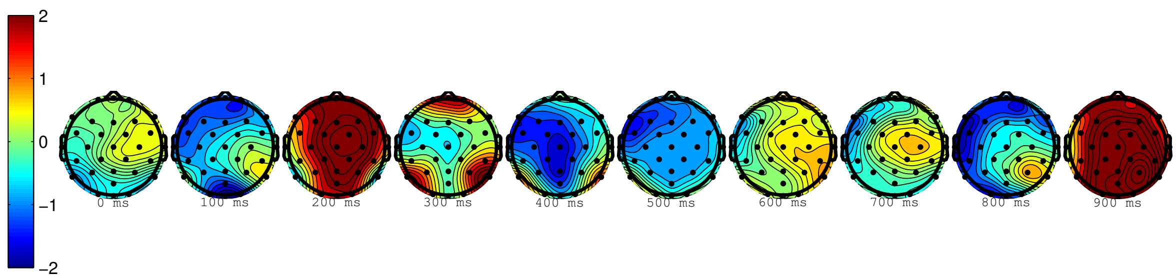
ERPs

Figure A.115: Reanalysis with subset of subjects (15), *the*, Whether vs. *the*, Control: topoplots

the Control



the, Whether



Difference plots

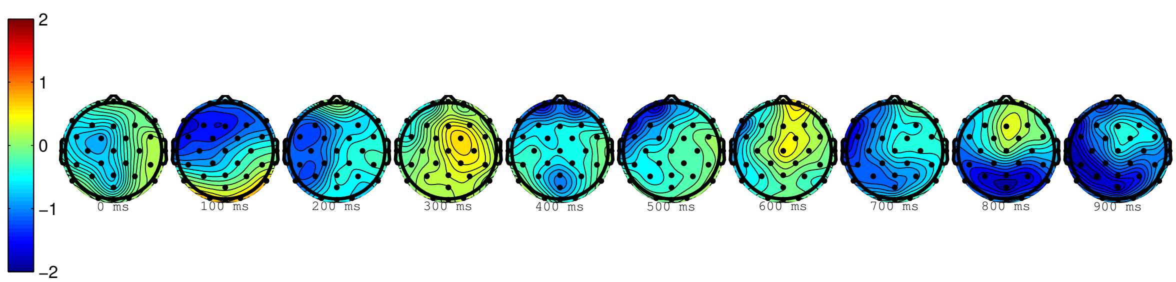


Figure A.116: Reanalysis with subset of subjects (15), *the*, Whether vs. *the*, Control: t_{max} permutation tests

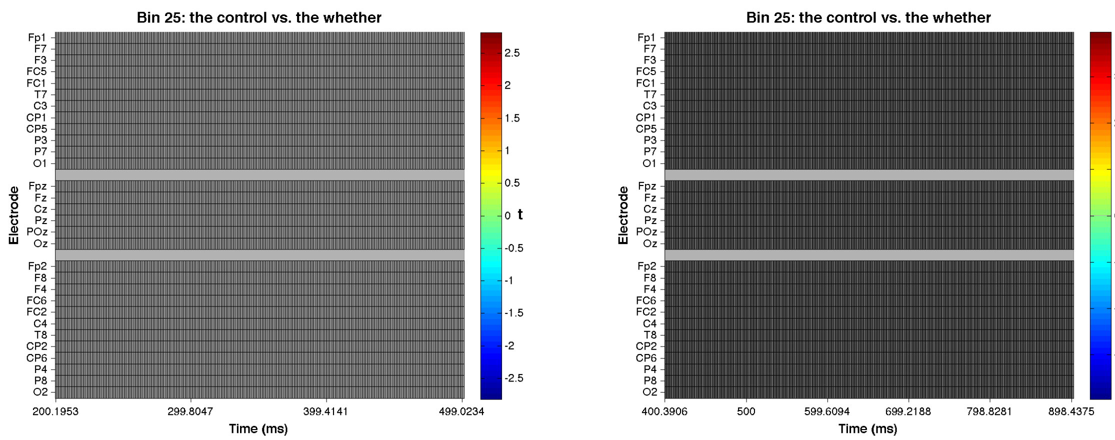
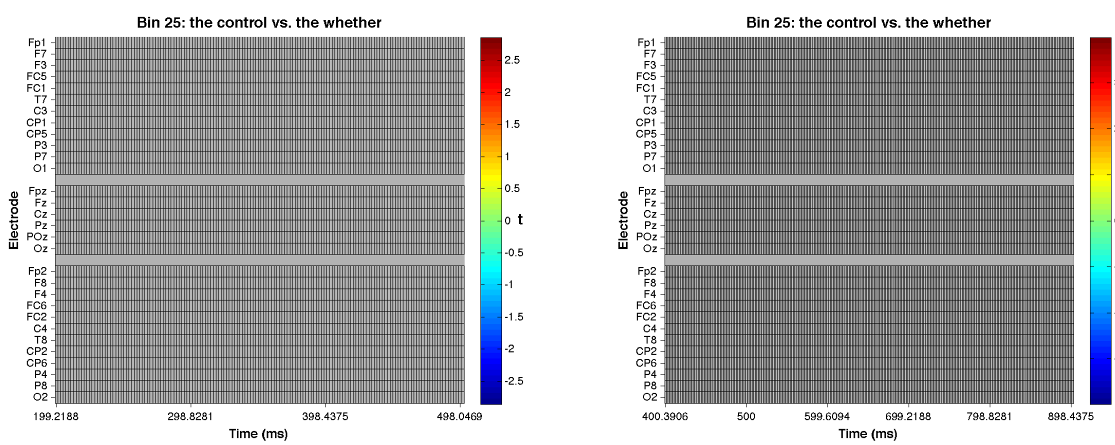


Figure A.117: Reanalysis with subset of subjects (15), *the*, Whether vs. *the*, Control: cluster mass permutation tests



TFRs

Figure A.118: Reanalysis with subset of subjects (15), First word after *whether* complementizer vs. Control: TFR

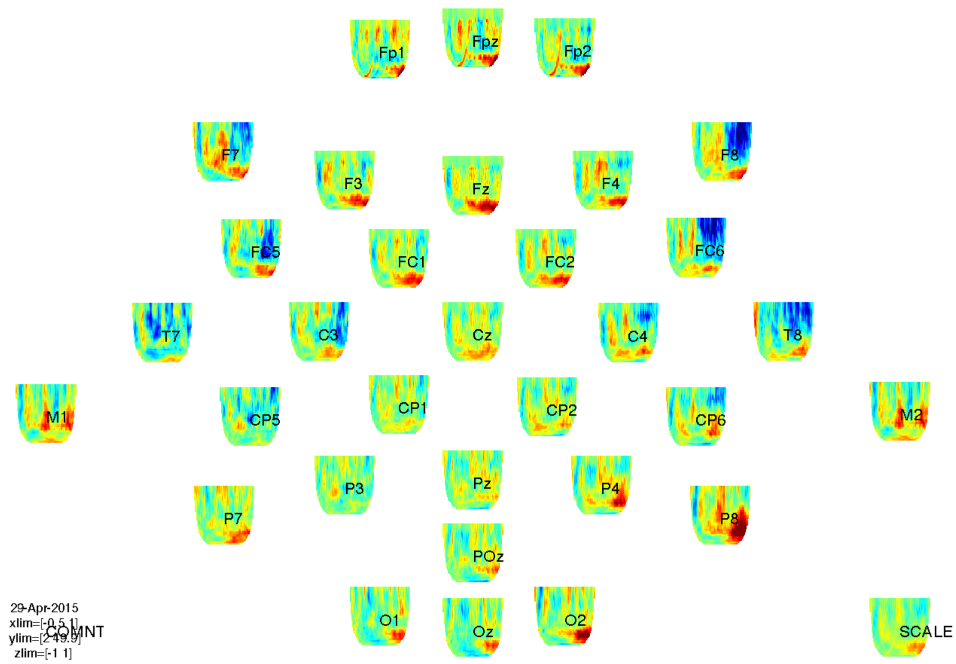


Figure A.119: Reanalysis with subset of subjects (15), First word after *whether* complementizer vs. Control: Alpha band (8-12Hz) masked stats TFR

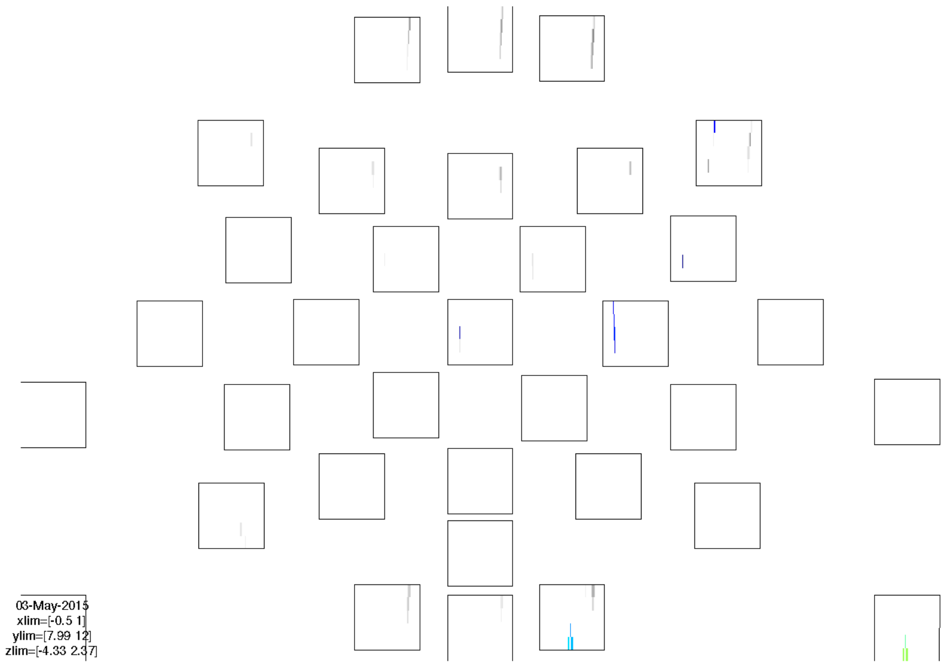


Figure A.120: Reanalysis with subset of subjects (15), First word after *whether* complementizer vs. Control: Alpha band (8-12Hz) masked stats TFR, significant channels

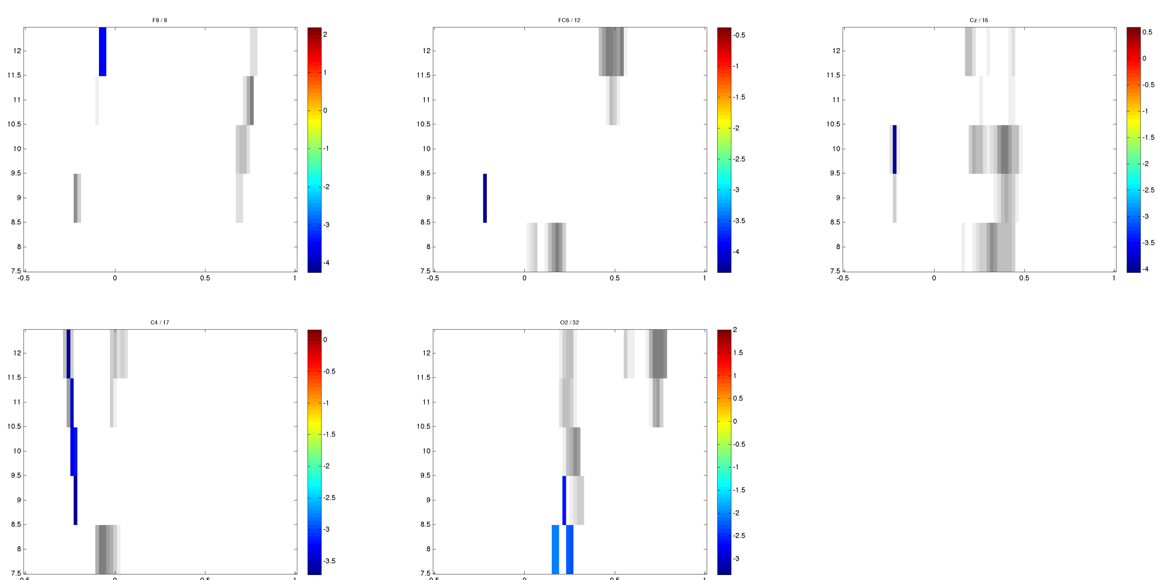


Figure A.121: Reanalysis with subset of subjects (15), First word after *whether* complementizer vs. Control: Lower Beta band (13-20Hz) masked stats TFR

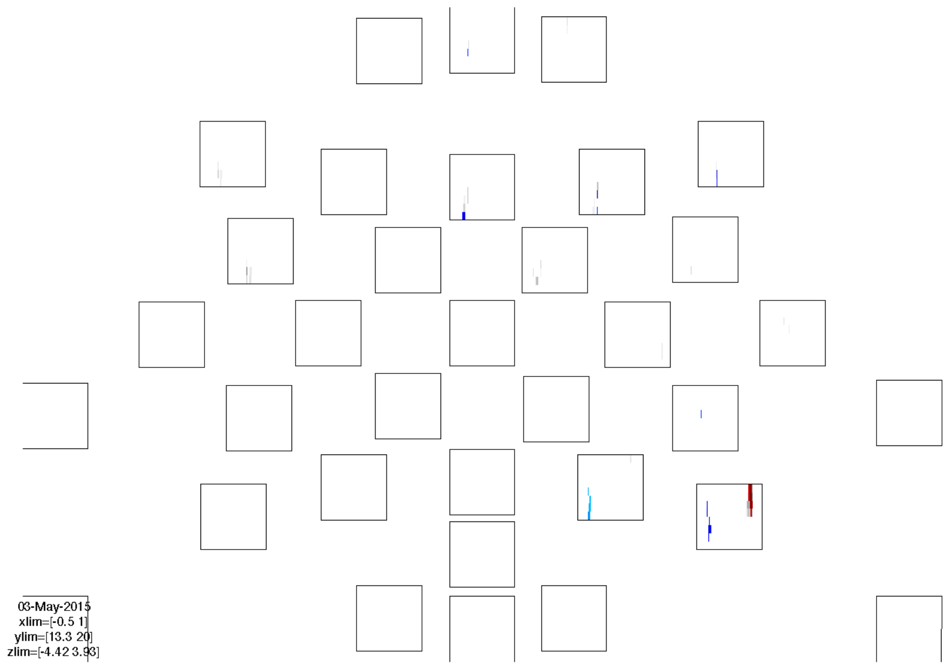


Figure A.122: Reanalysis with subset of subjects (15), First word after *whether* complementizer vs. Control: Lower Beta band (13-20Hz) masked stats TFR, significant channels

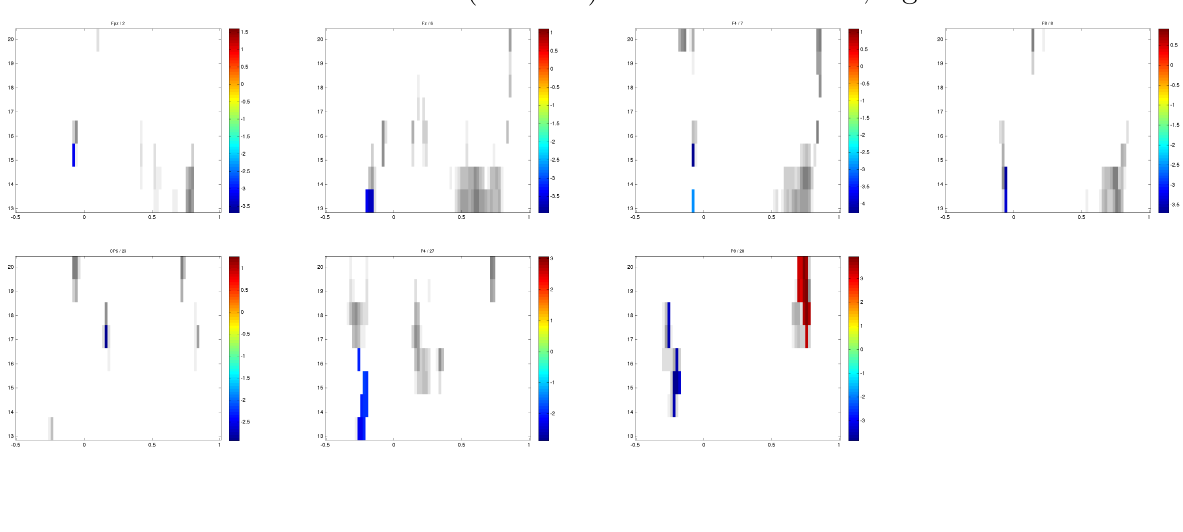


Figure A.123: Reanalysis with subset of subjects (15), First word after *whether* complementizer vs. Control: Upper Beta band (21-30Hz) masked stats TFR

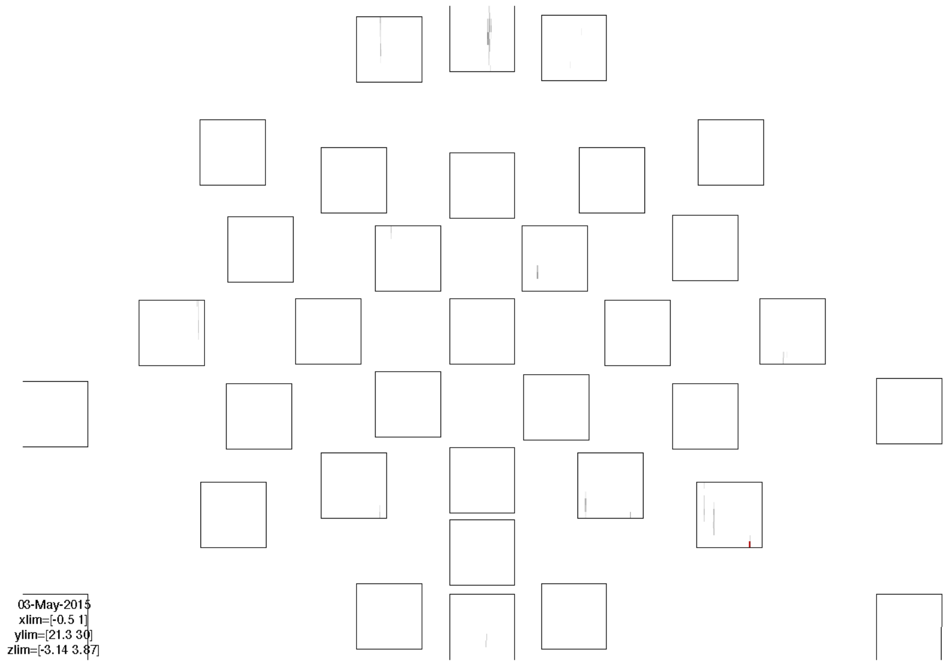
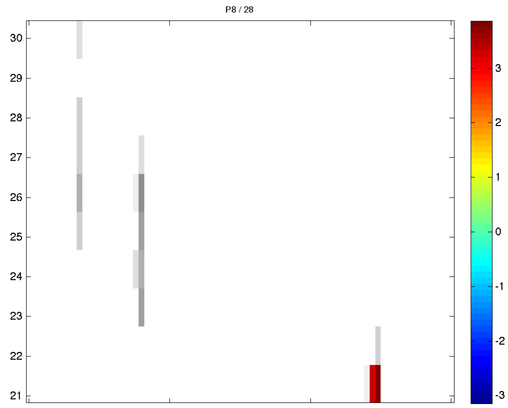


Figure A.124: Reanalysis with subset of subjects (15), First word after *whether* complementizer vs. Control: Upper Beta band (21-30Hz) masked stats TFR, significant channels



A.0.2 Reanalysis with subset of subjects (13): ERPs and TFRs

Given that the canonical event-related responses to the experimental stimuli were not found in all cases, a second analysis was run in which subjects' individual ERPs were examined, and a subset of subjects were selected. In this case, the result was a down-selected group of 13 subjects, whose EEG response to these well-vetted experimental conditions appeared typical (i.e., had the canonical N1/P2 complex, lacked noise in the signal). By analyzing this group we can distinguish whether a lack of expected ERP response in the larger group is a result of noise in the data of certain subjects, or a more broad data quality issue. Down-selecting the subject data will reduce power in the analysis, however the size of this group (13 subjects) is within the lower bounds of the typical group size in which ERPs like the P600 are apparent.

Reanalysis with subset of subjects (13): Garden Path

GPC The woman heard that the broker intended *to* conceal the transaction at the meeting.
GPV The woman heard that the broker persuaded *to* conceal the transaction was sent to jail.

ERPs

Figure A.125: Reanalysis with subset of subjects (13), Garden Path Violation: ERPs

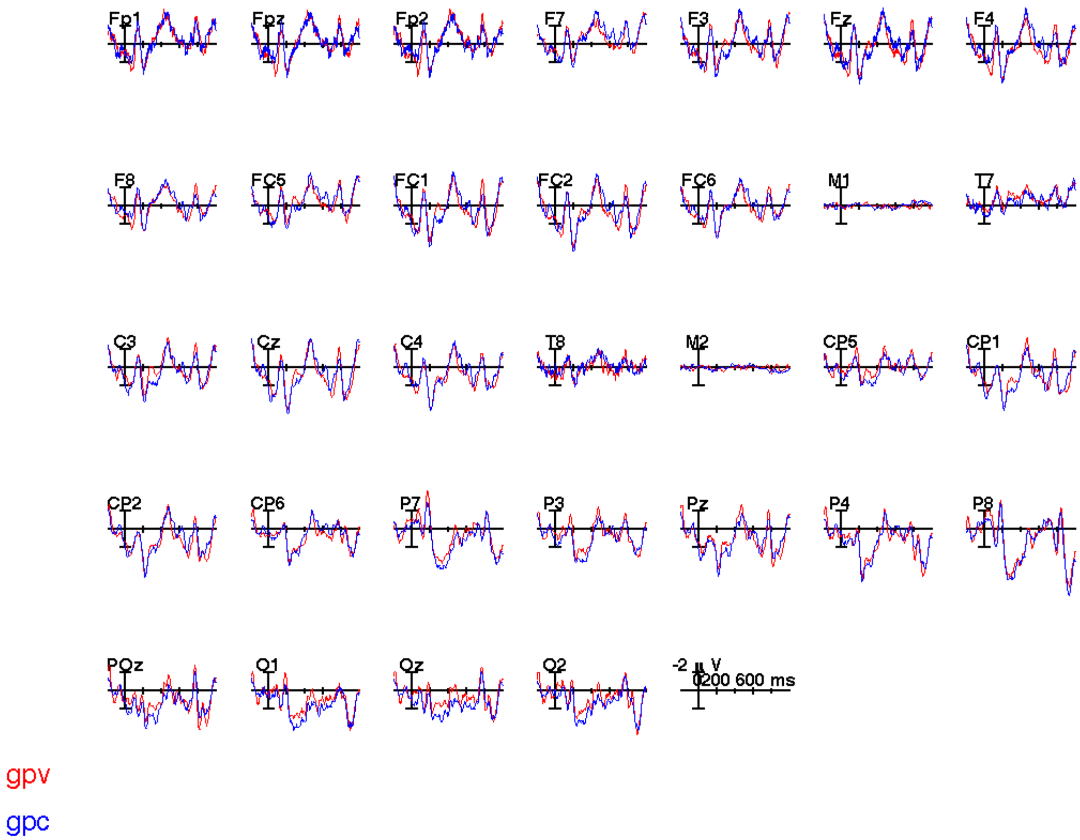
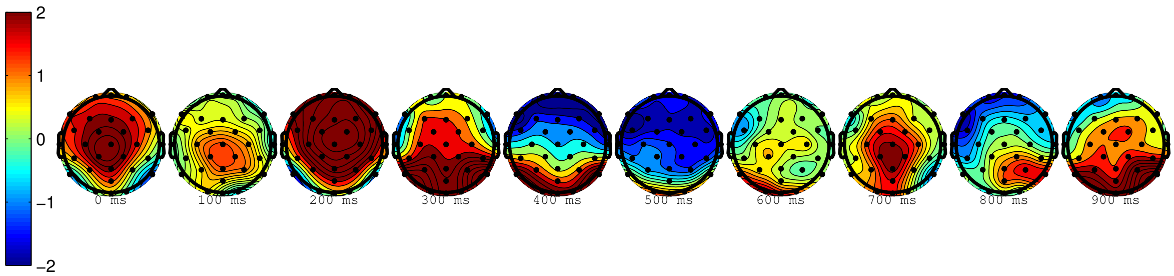
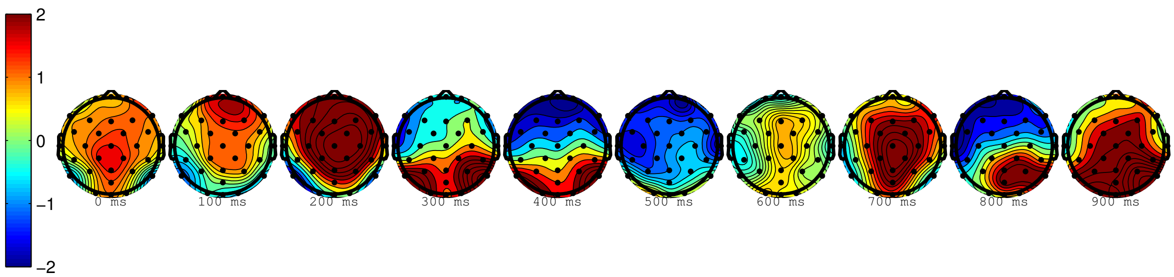


Figure A.126: Reanalysis with subset of subjects (13), Garden Path Violation: topoplots

Garden Path Control



Garden Path Violation



Difference plots

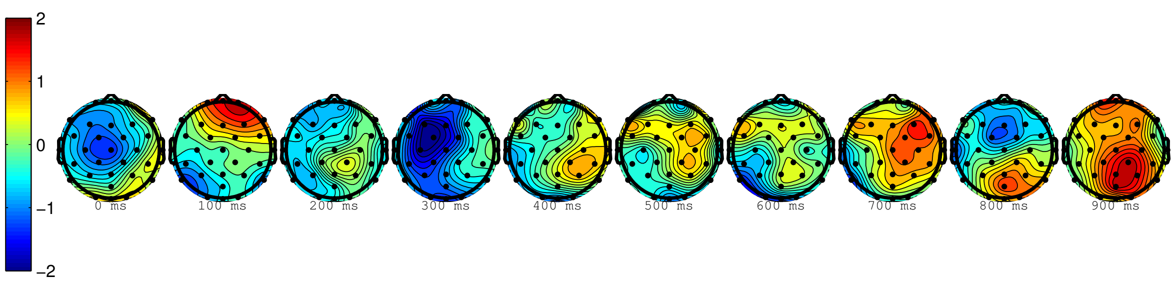


Figure A.127: Reanalysis with subset of subjects (13), Garden Path Violation: t_{max} permutation tests

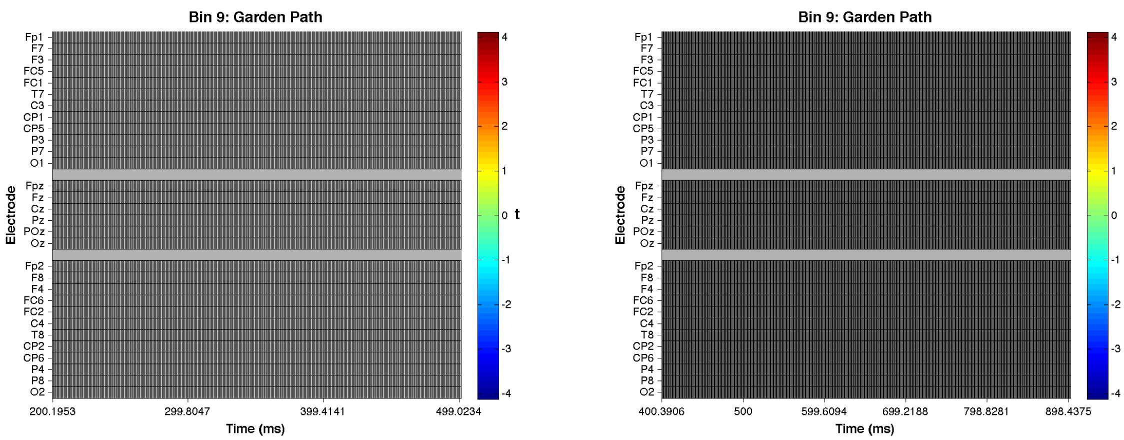
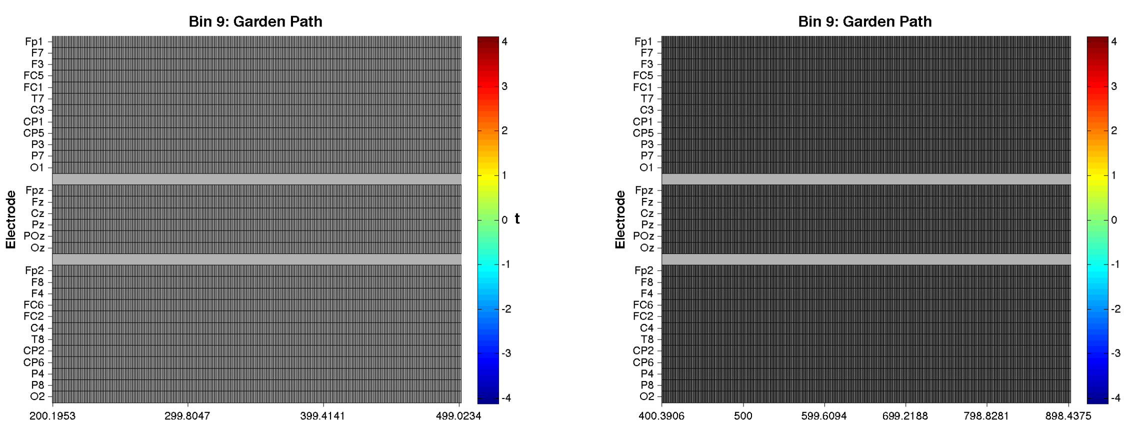


Figure A.128: Reanalysis with subset of subjects (13), Garden Path Violation: cluster mass permutation tests



TFRs

Figure A.129: Reanalysis with subset of subjects (13), Garden Path Violation: TFR

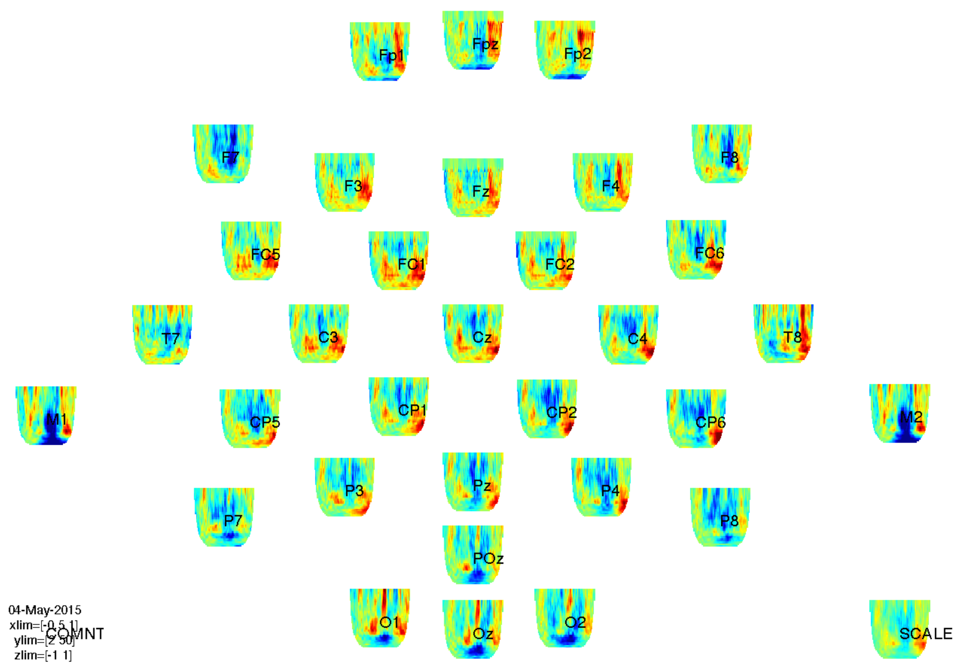


Figure A.130: Reanalysis with subset of subjects (13), Garden Path Violation: Theta band (4-7Hz) masked stats TFR

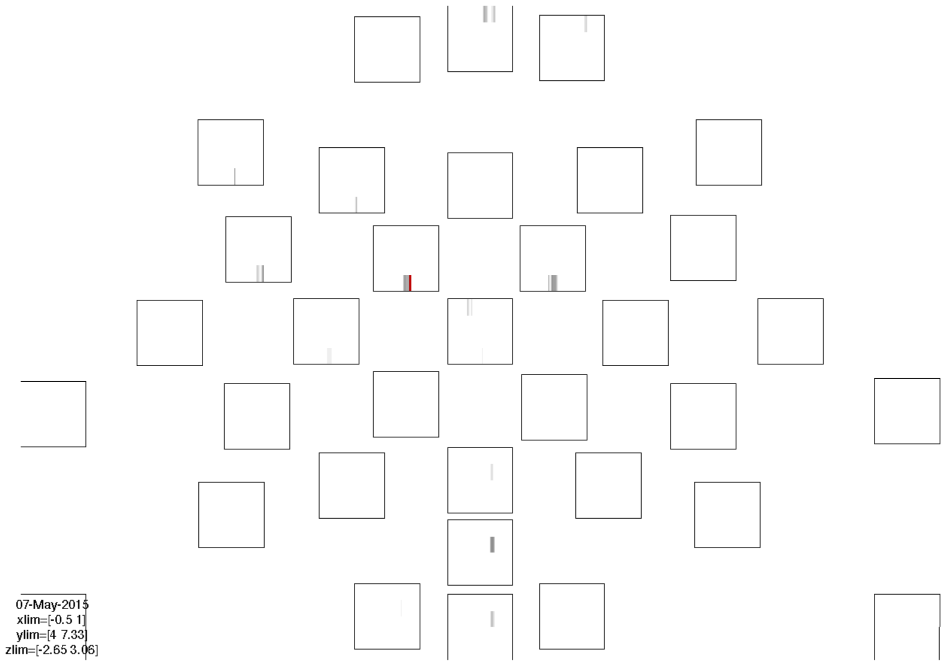


Figure A.131: Reanalysis with subset of subjects (13), Garden Path Violation: Theta band (4-7Hz) masked stats TFR, significant channels

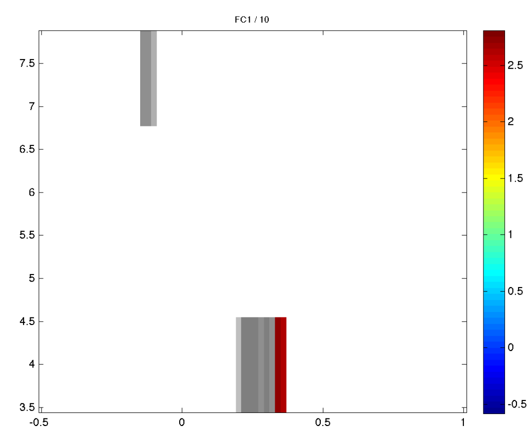


Figure A.132: Reanalysis with subset of subjects (13), Garden Path Violation: Alpha band (8-12Hz) masked stats TFR

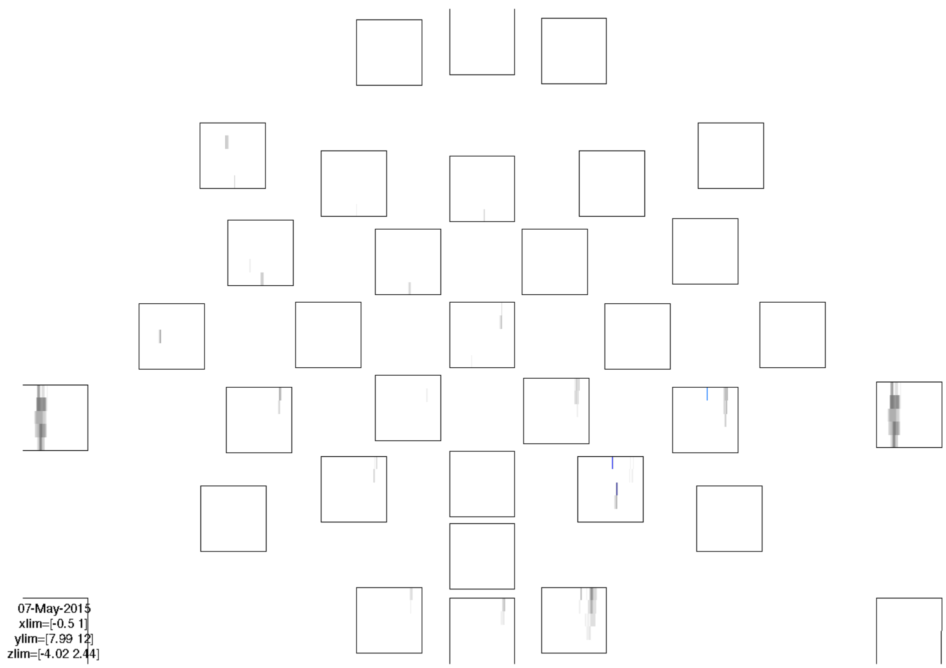


Figure A.133: Reanalysis with subset of subjects (13), Garden Path Violation: Alpha band (8-12Hz) masked stats TFR, significant channels

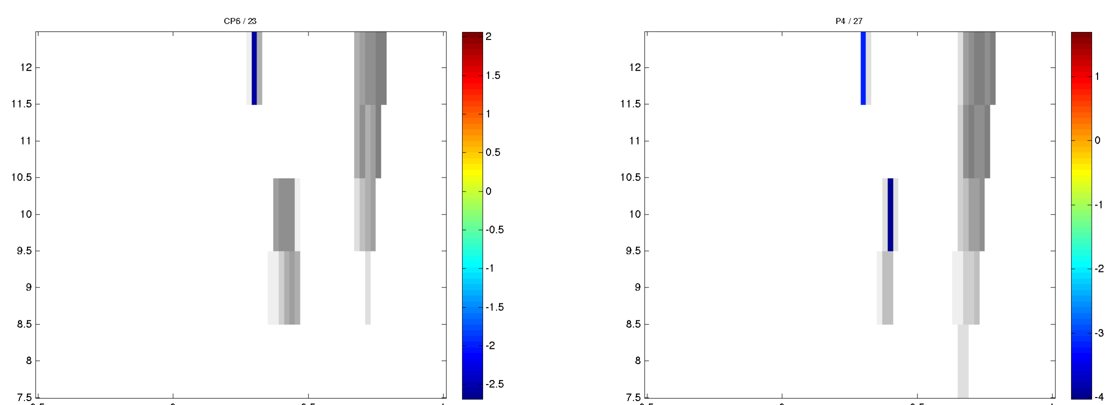


Figure A.134: Reanalysis with subset of subjects (13), Garden Path Violation: Lower Beta band (13-20Hz) masked stats TFR

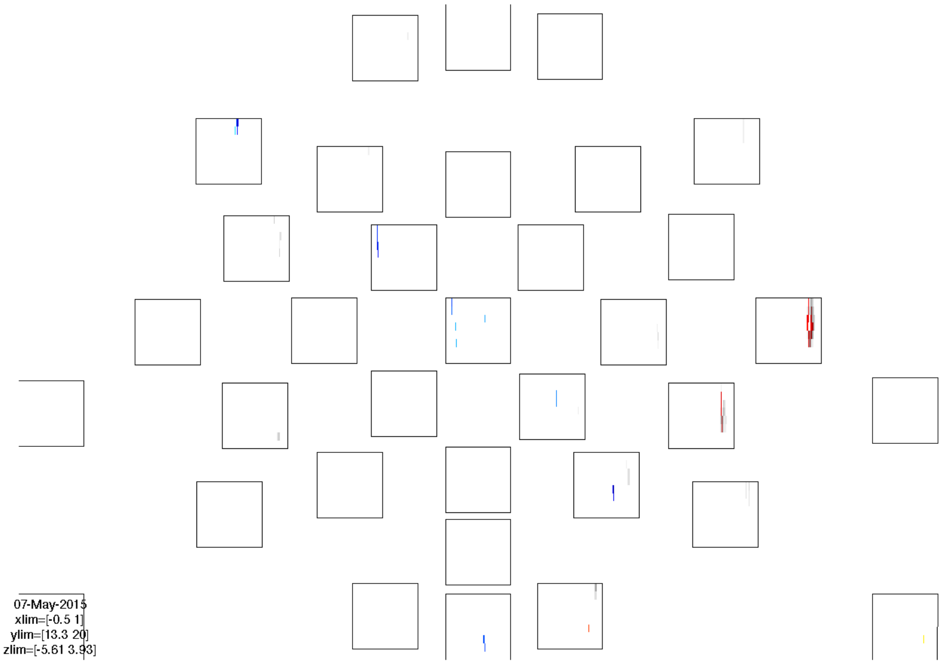


Figure A.135: Reanalysis with subset of subjects (13), Garden Path Violation: Lower Beta band (13-20Hz) masked stats TFR, significant channels

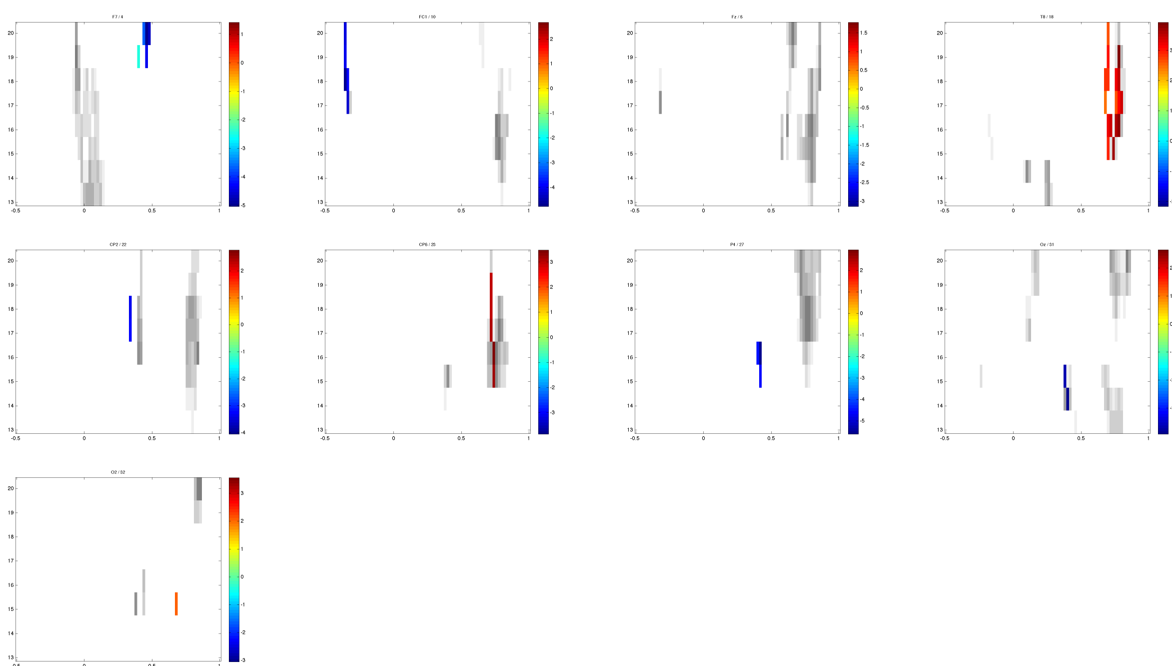


Figure A.136: Reanalysis with subset of subjects (13), Garden Path Violation: Upper Beta band (21-30Hz) masked stats TFR

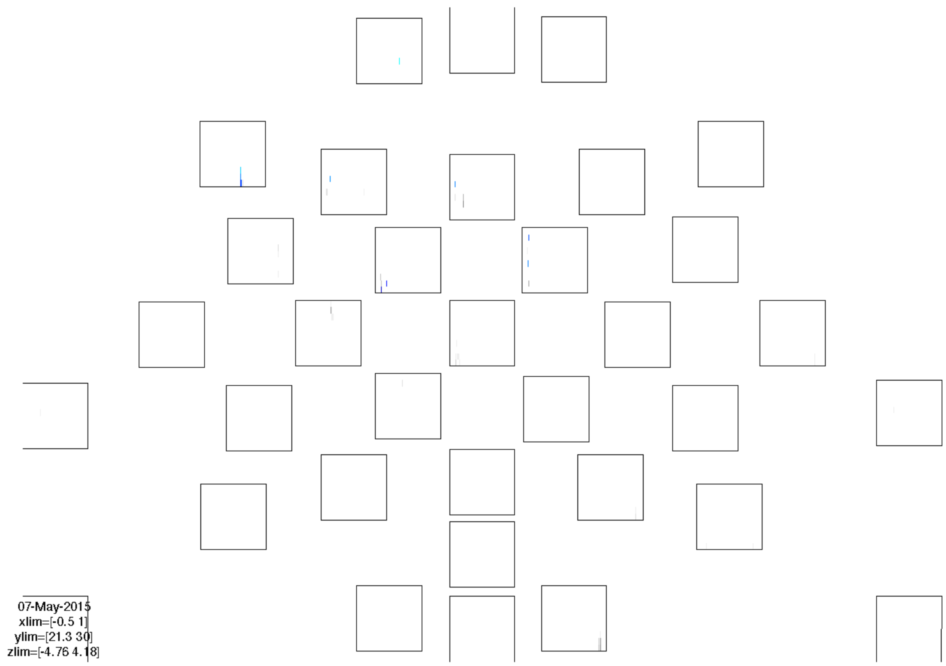


Figure A.137: Reanalysis with subset of subjects (13), Garden Path Violation: Upper Beta band (21-30Hz) masked stats TFR, significant channels

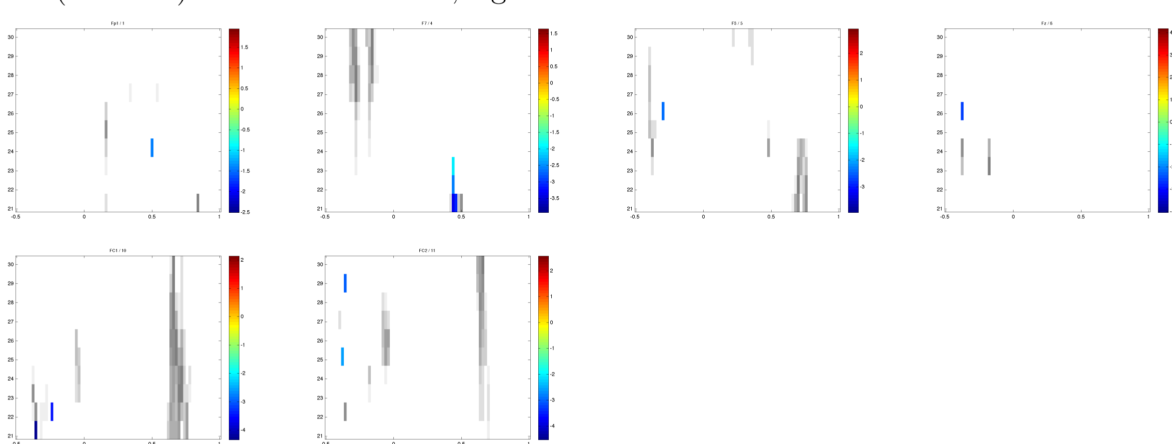
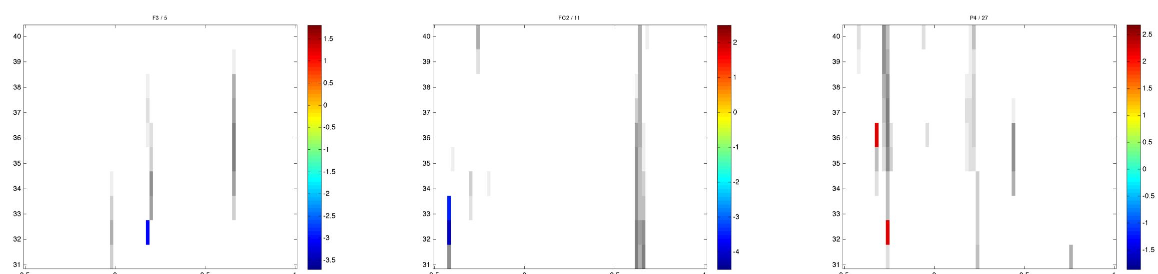


Figure A.138: Reanalysis with subset of subjects (13), Garden Path Violation: Gamma band (31-40Hz) masked stats TFR

Figure A.139: Reanalysis with subset of subjects (13), Garden Path Violation: Gamma band (31-40Hz) masked stats TFR, significant channels



Reanalysis with subset of subjects (13): Thematic P600s

THC The woman suspected that the murder was *witnessed* by three bystanders.
THV The woman suspected that the murder was *witnessing* the three bystanders.

ERPs

Figure A.140: Reanalysis with subset of subjects (13), Thematic P600: ERPs

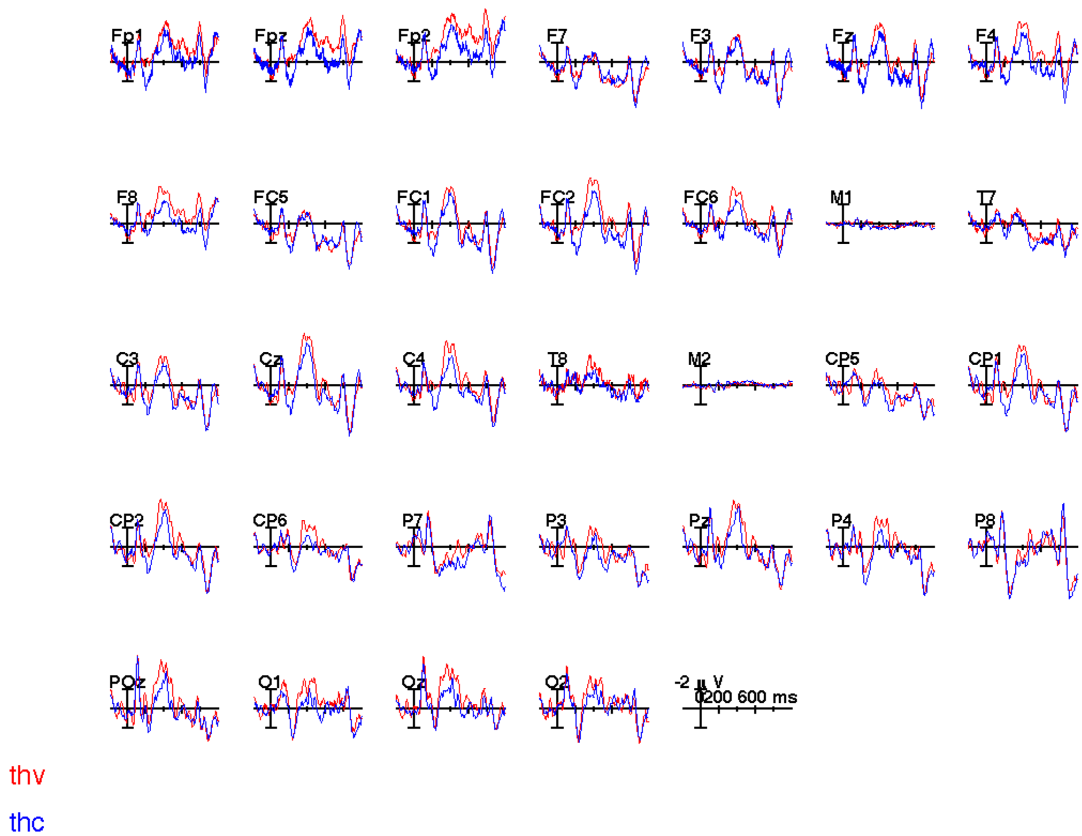
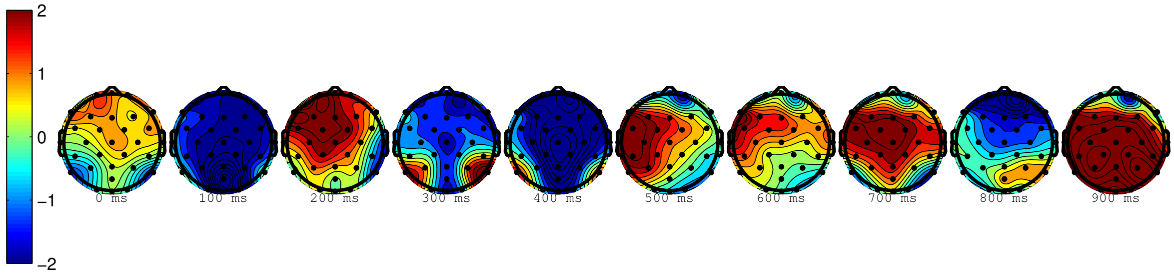
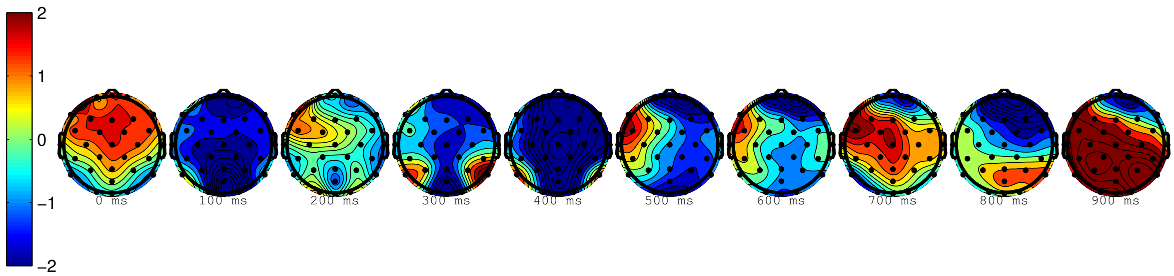


Figure A.141: Reanalysis with subset of subjects (13), Thematic P600: topoplots

Thematic P600 Control



Thematic P600



Difference plots

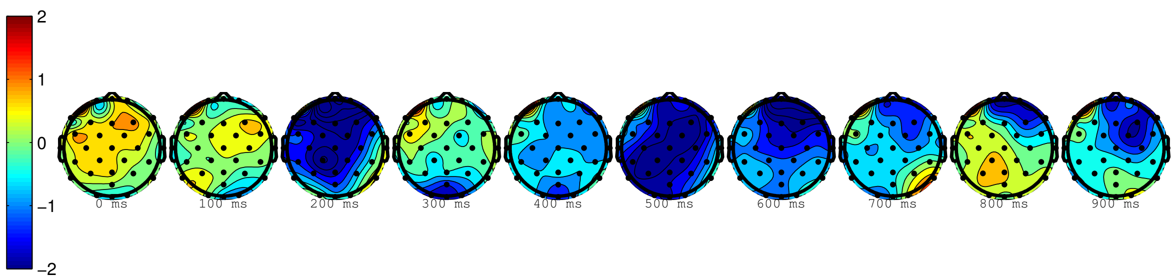


Figure A.142: Reanalysis with subset of subjects (13), Thematic P600: t_{max} permutation tests

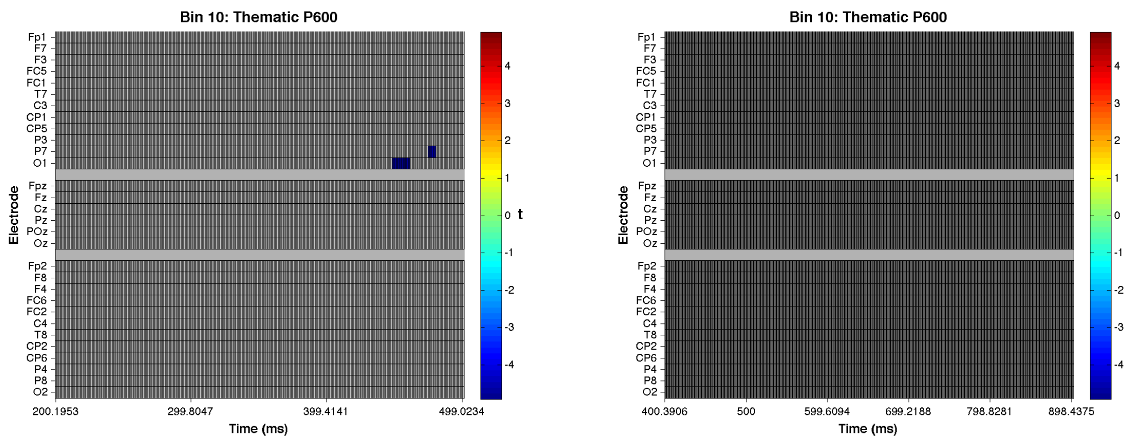
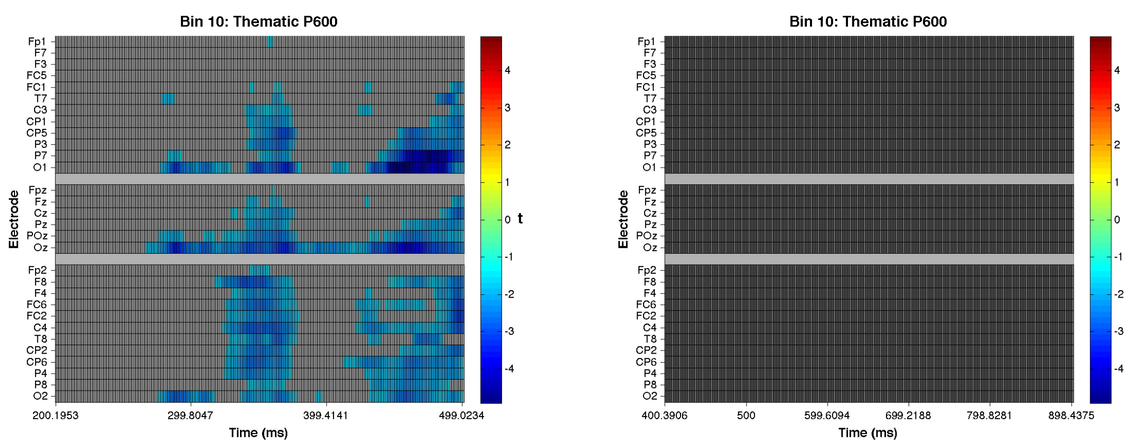


Figure A.143: Reanalysis with subset of subjects (13), Thematic P600: cluster mass permutation tests



TFRs

Figure A.144: Thematic P600: TFR

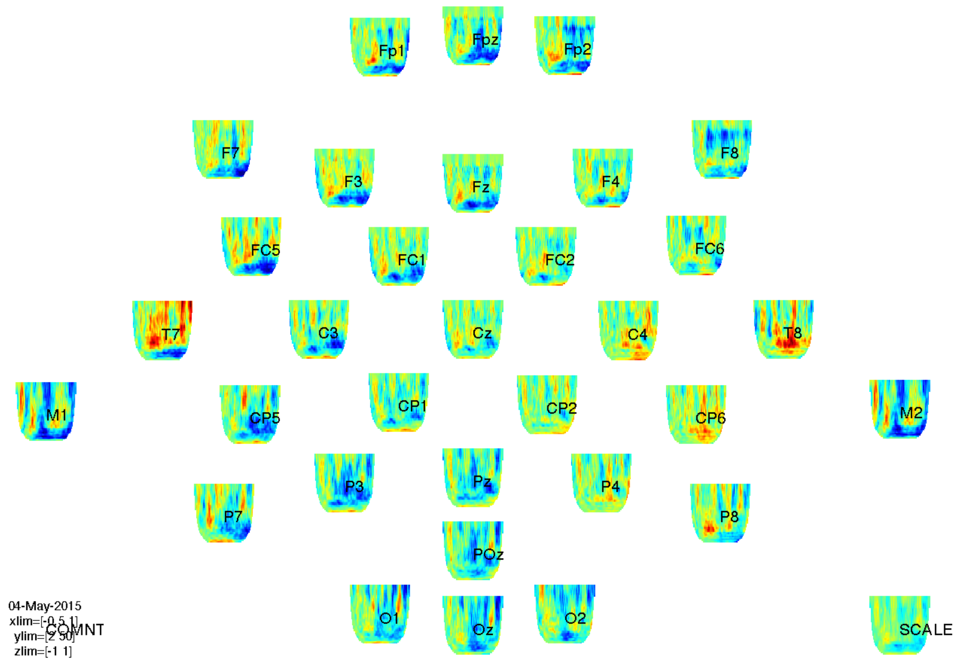


Figure A.145: Reanalysis with subset of subjects (13), Thematic P600: Alpha band (8-12Hz) masked stats TFR

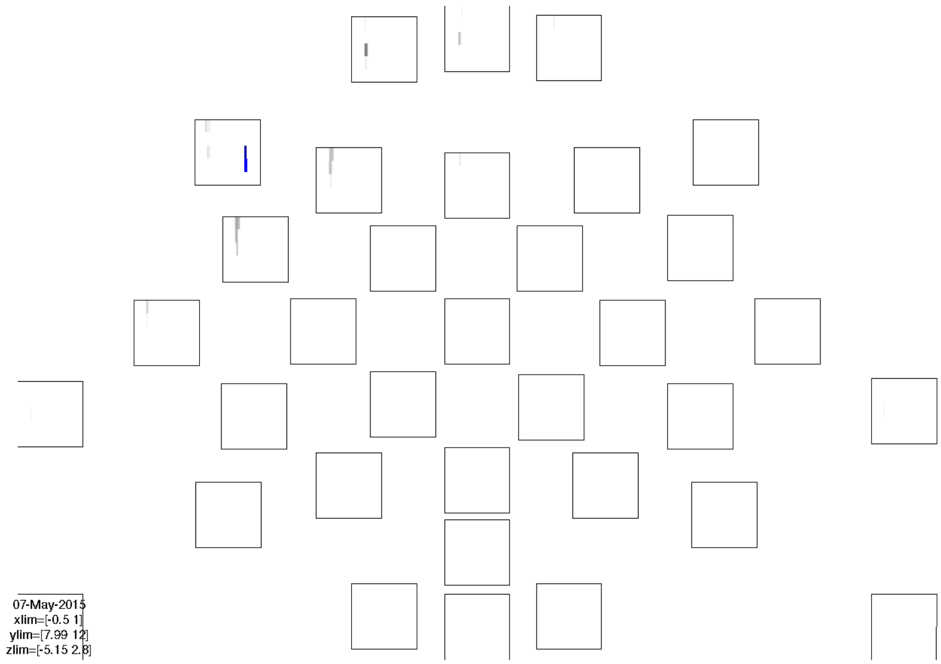


Figure A.146: Reanalysis with subset of subjects (13), Thematic P600: Alpha band (8-12Hz) masked stats TFR, significant channels

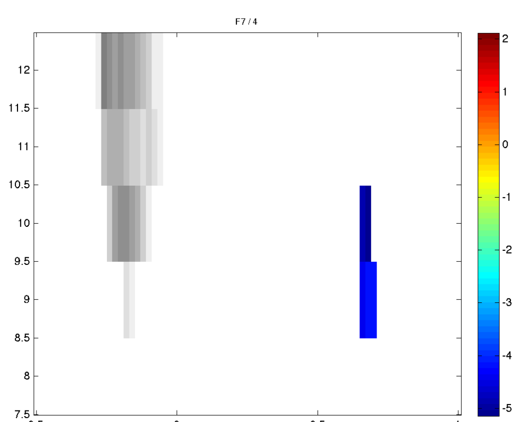


Figure A.147: Reanalysis with subset of subjects (13), Thematic P600: Lower Beta band (13-20Hz) masked stats TFR

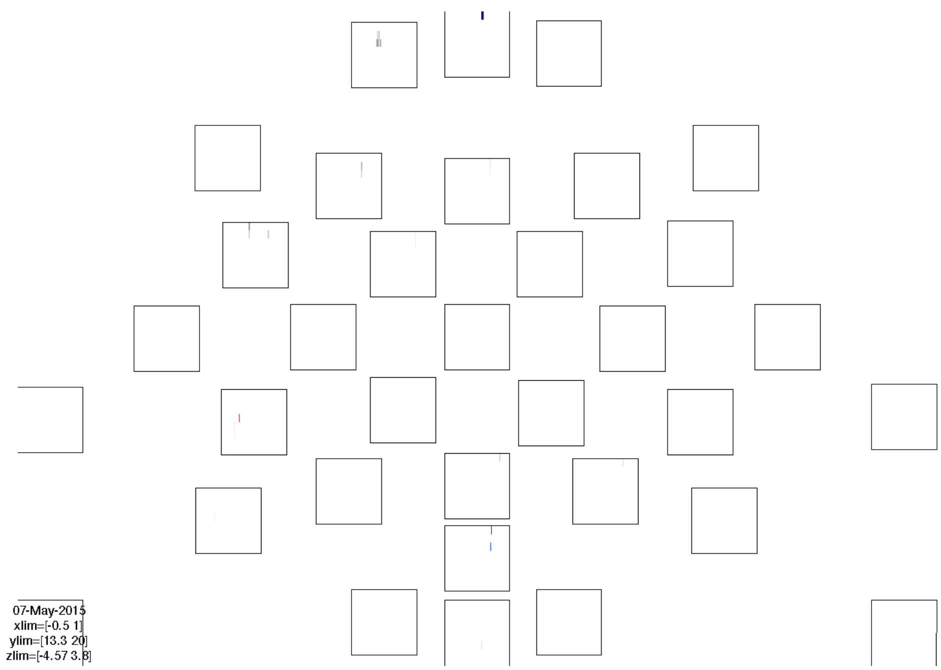


Figure A.148: Reanalysis with subset of subjects (13), Thematic P600: Lower Beta band (13-20Hz) masked stats TFR, significant channels

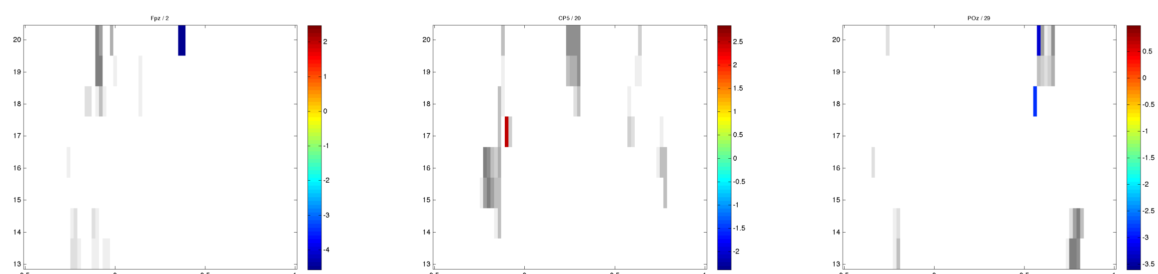


Figure A.149: Reanalysis with subset of subjects (13), Thematic P600: Upper Beta band (21-30Hz) masked stats TFR

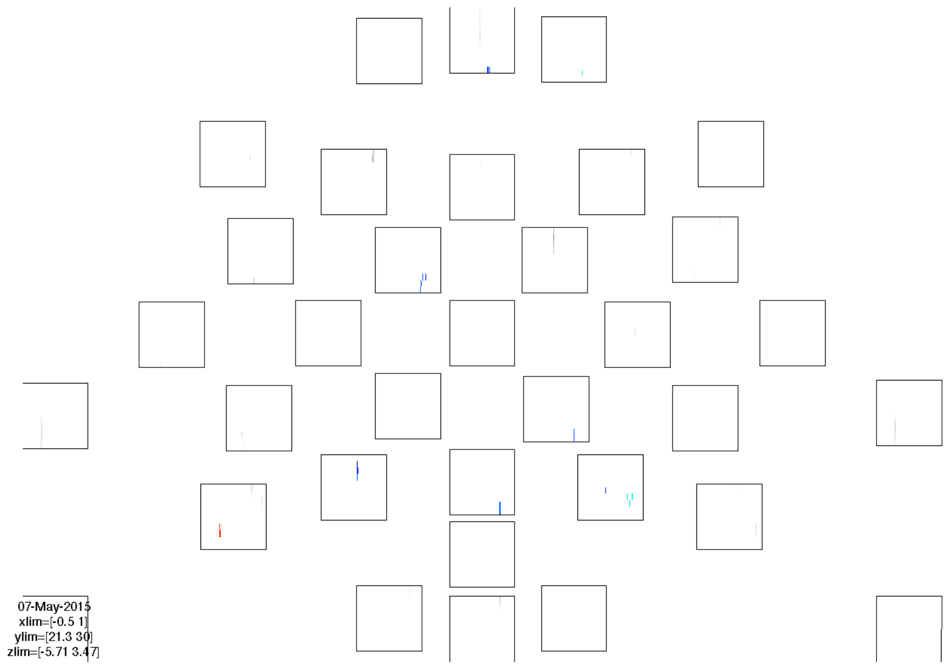
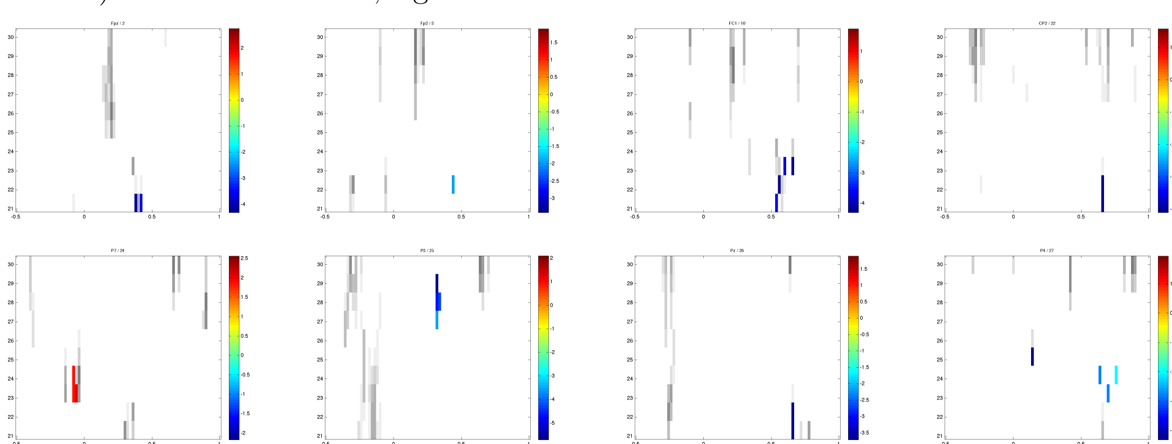


Figure A.150: Reanalysis with subset of subjects (13), Thematic P600: Upper Beta band (21-30Hz) masked stats TFR, significant channels



Reanalysis with subset of subjects (13): Island Violations

ISC I wonder whether the candidate was annoyed *when* his son was questioned by one of his staff.
ISV I wonder who the candidate was annoyed *when* his son was questioned by.

ERPs

Figure A.151: Reanalysis with subset of subjects (13), Island Violation: ERPs

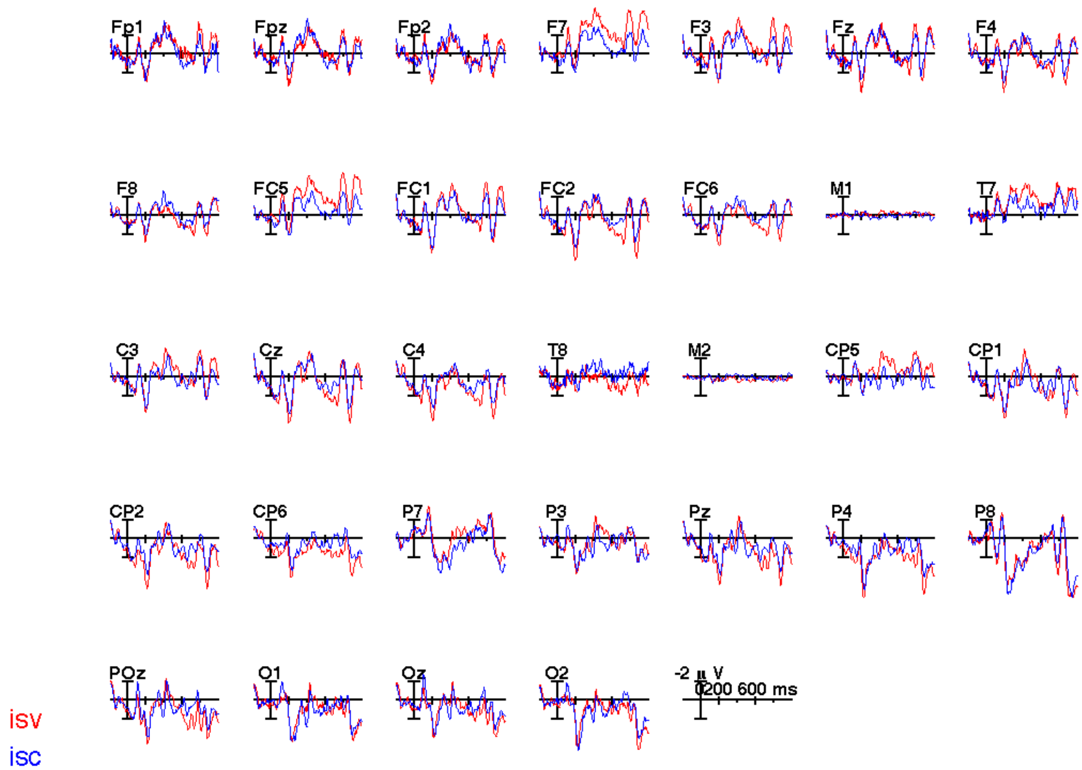
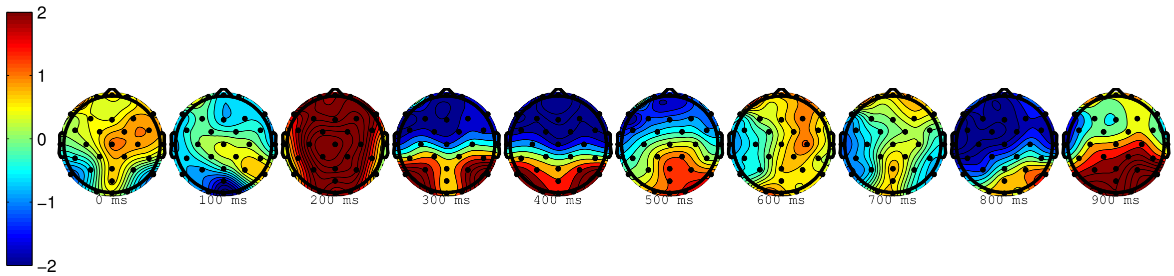
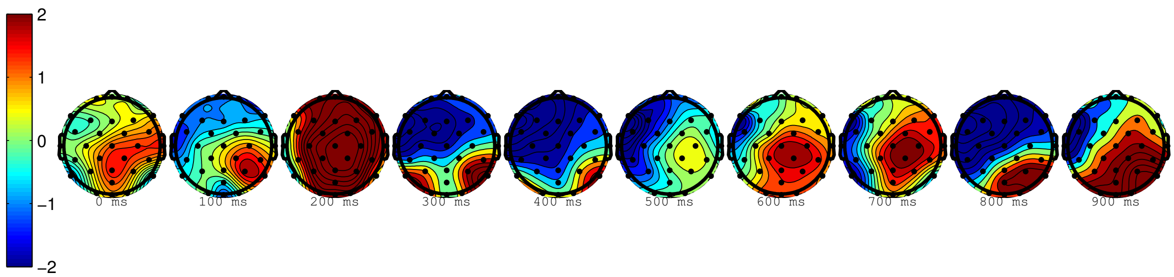


Figure A.152: Reanalysis with subset of subjects (13), Island Violation: topoplots

Island Control



Island Violation



Difference plots

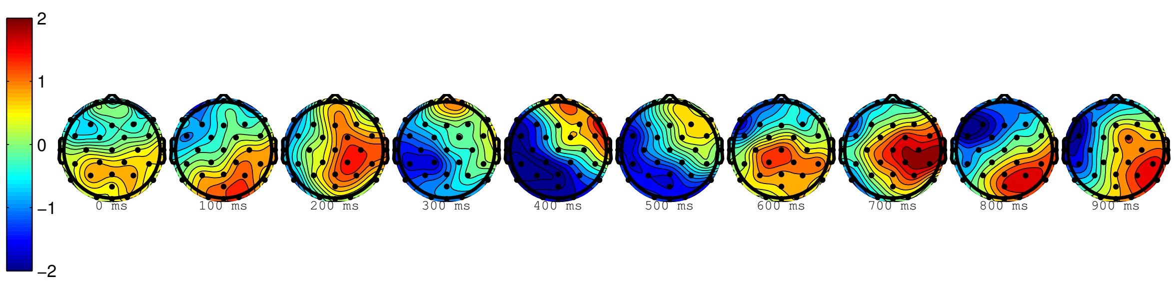


Figure A.153: Reanalysis with subset of subjects (13), Island Violation: t_{max} permutation tests

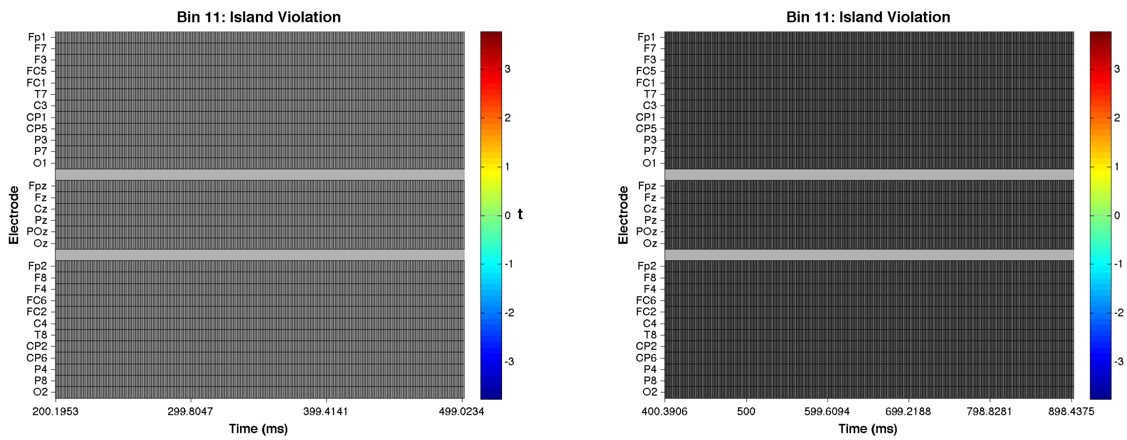
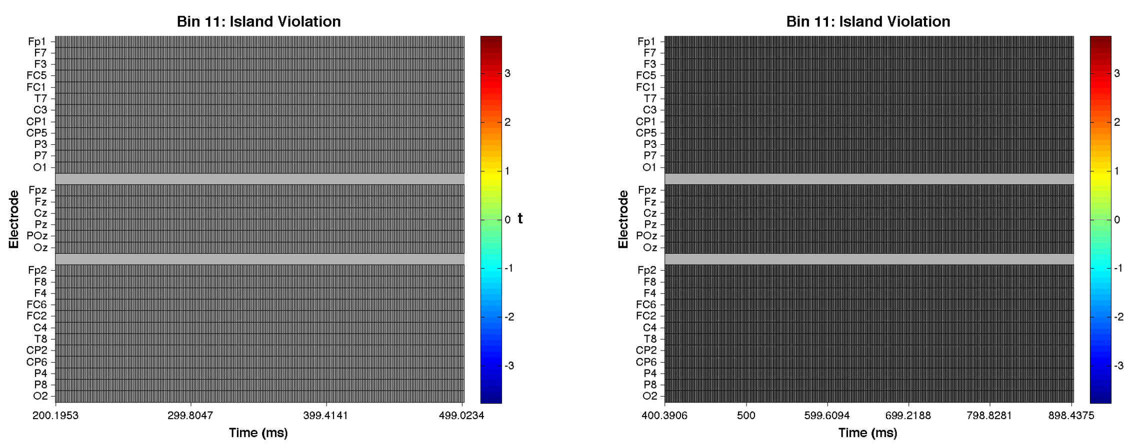


Figure A.154: Reanalysis with subset of subjects (13), Island Violation: cluster mass permutation tests



TFRs

Figure A.155: Island Violation: TFR

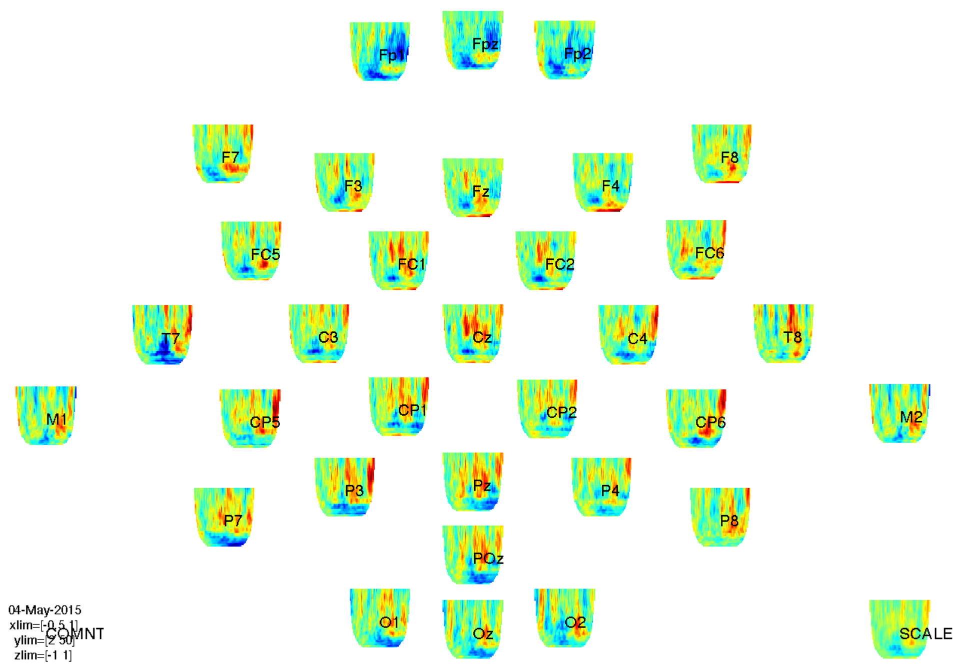


Figure A.156: Reanalysis with subset of subjects (13), Island Violation: Theta band (4-7Hz) masked stats TFR

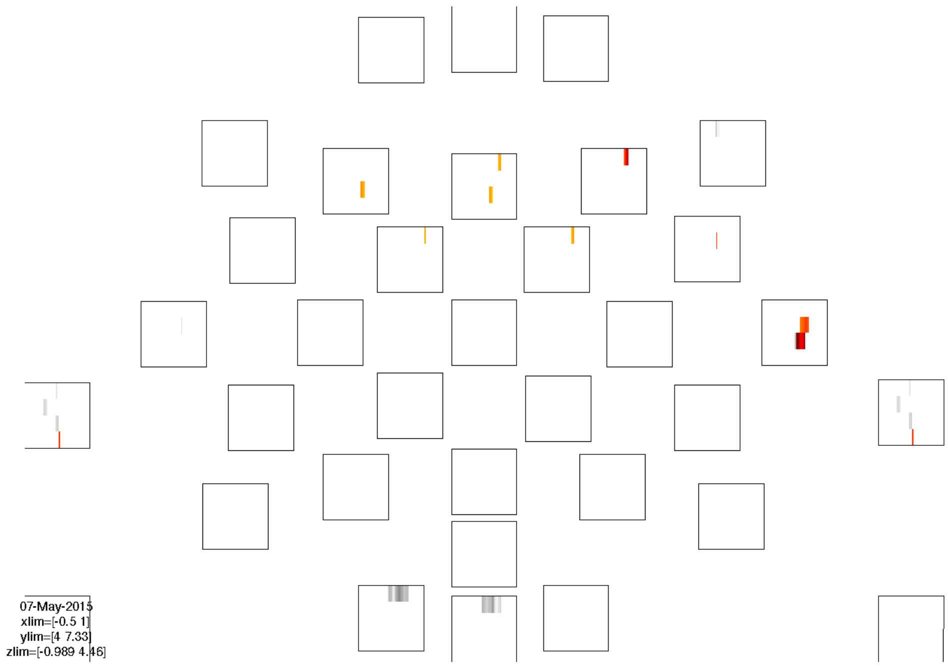


Figure A.157: Reanalysis with subset of subjects (13), Island Violation: Theta band (4-7Hz) masked stats TFR, significant channels

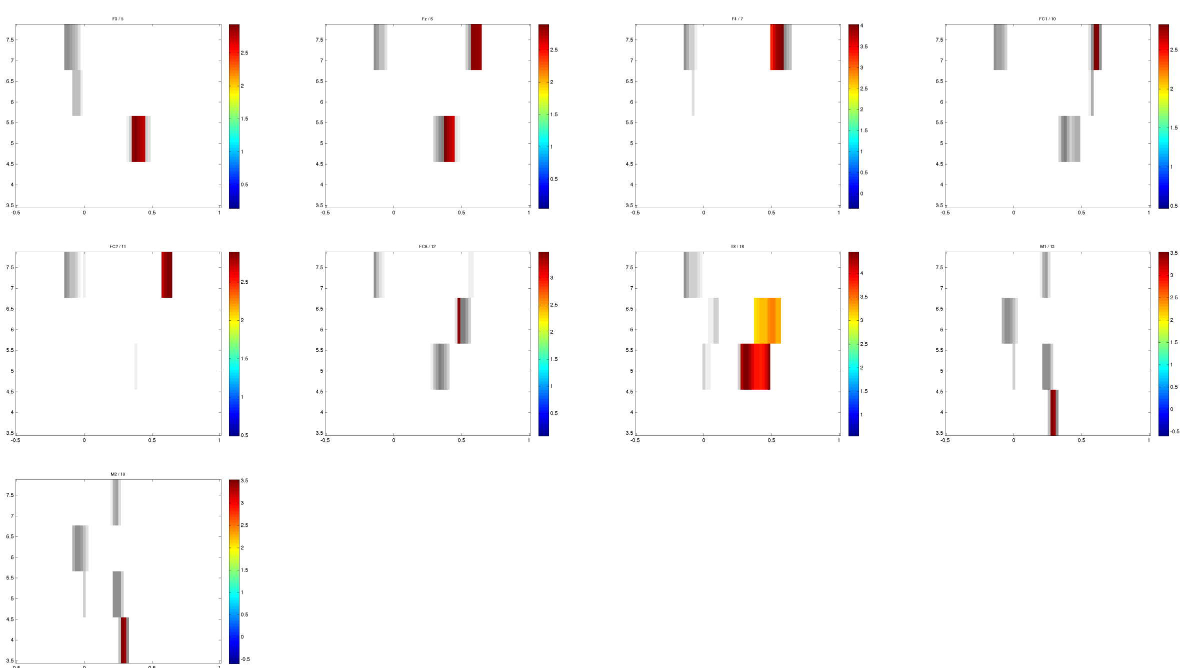


Figure A.158: Reanalysis with subset of subjects (13), Island Violation: Lower Beta band (13-20Hz) masked stats TFR

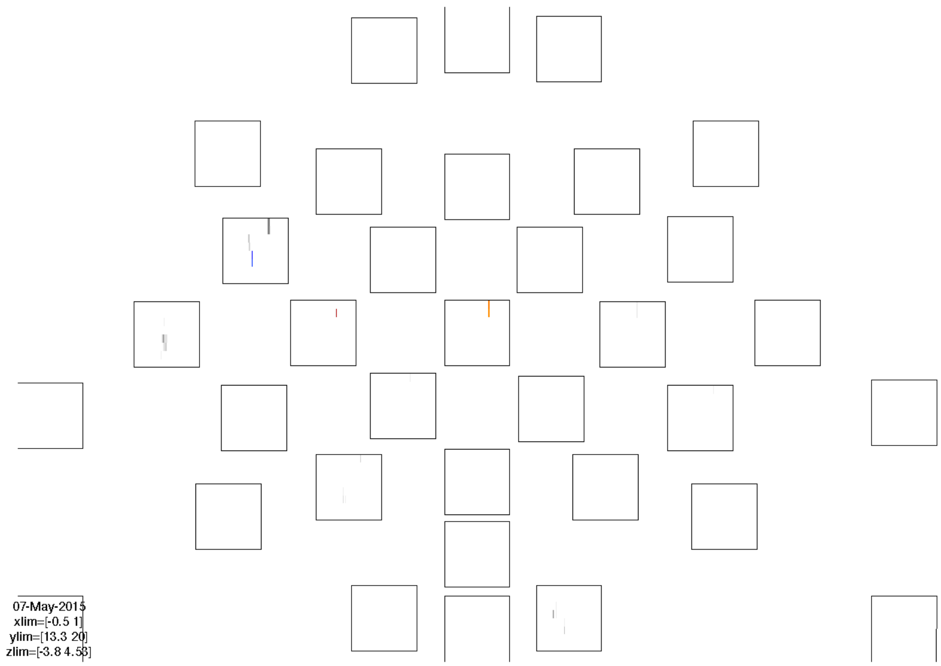


Figure A.159: Reanalysis with subset of subjects (13), Island Violation: Lower Beta band (13-20Hz) masked stats TFR, significant channels

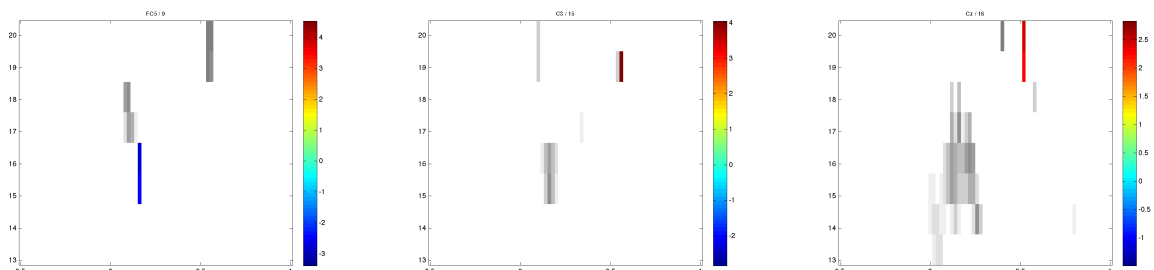


Figure A.160: Reanalysis with subset of subjects (13), Island Violation: Upper Beta band (21-30Hz) masked stats TFR

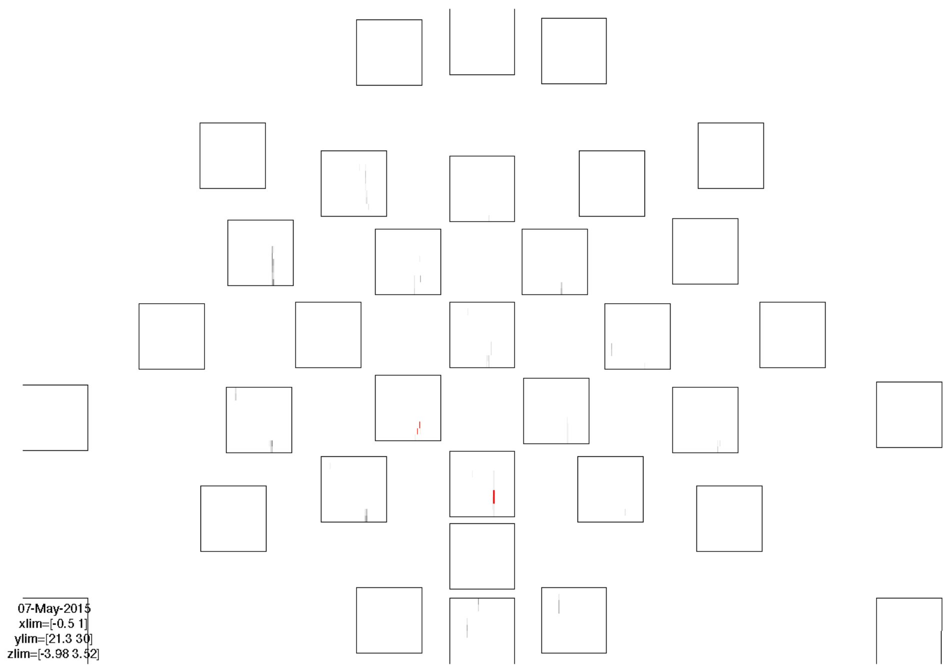


Figure A.161: Reanalysis with subset of subjects (13), Island Violation: Upper Beta band (21-30Hz) masked stats TFR, significant channels

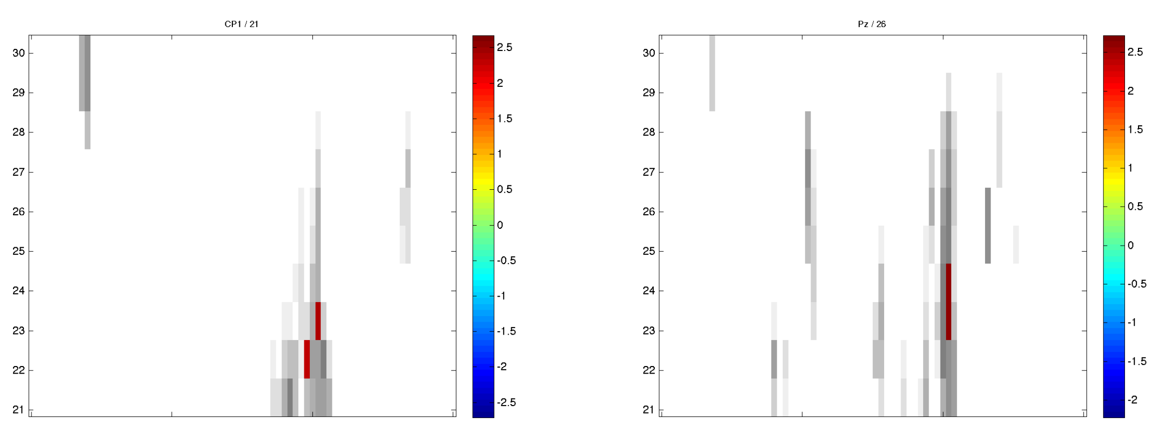


Figure A.162: Reanalysis with subset of subjects (13), Island Violation: Gamma band (31-40Hz) masked stats TFR

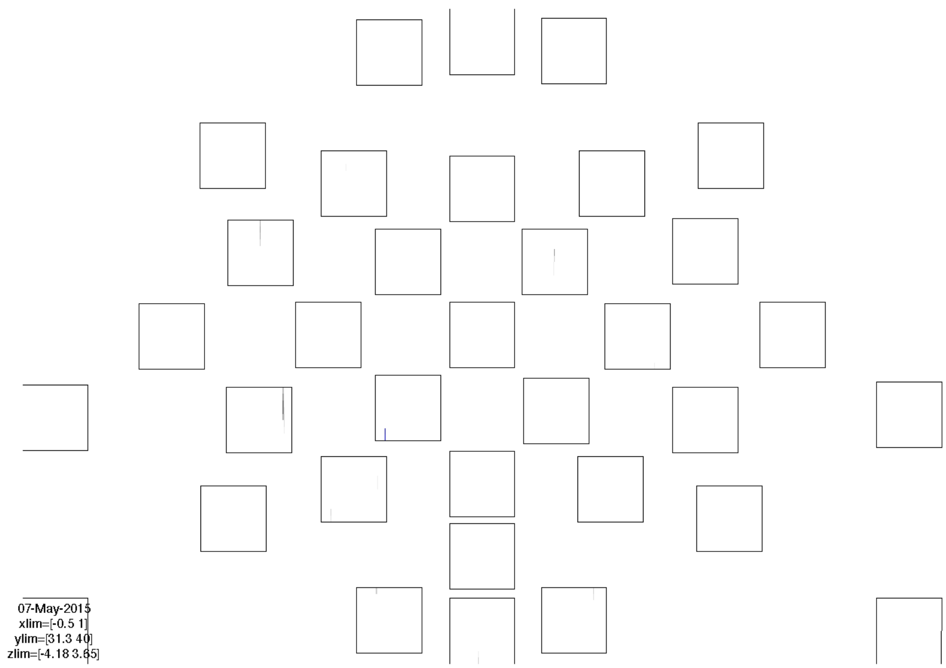
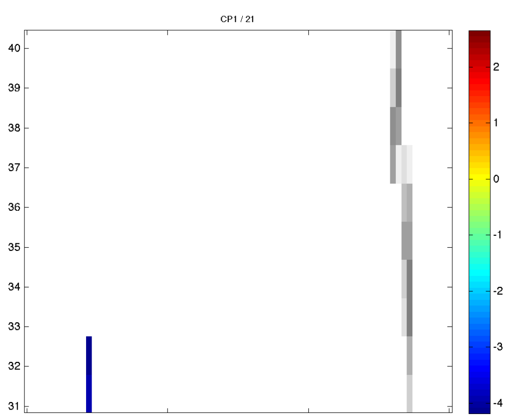


Figure A.163: Reanalysis with subset of subjects (13), Island Violation: Gamma band (31-40Hz) masked stats TFR, significant channels



Reanalysis with subset of subjects (13), Phrase Structure Violations

PSC Jill heard that the students discussed Frank's *speech* about migrants.
PSV Jill heard that the students discussed Frank's *about* speech migrants.

ERPs

Figure A.164: Reanalysis with subset of subjects (13), Phrase Structure Violation: ERPs

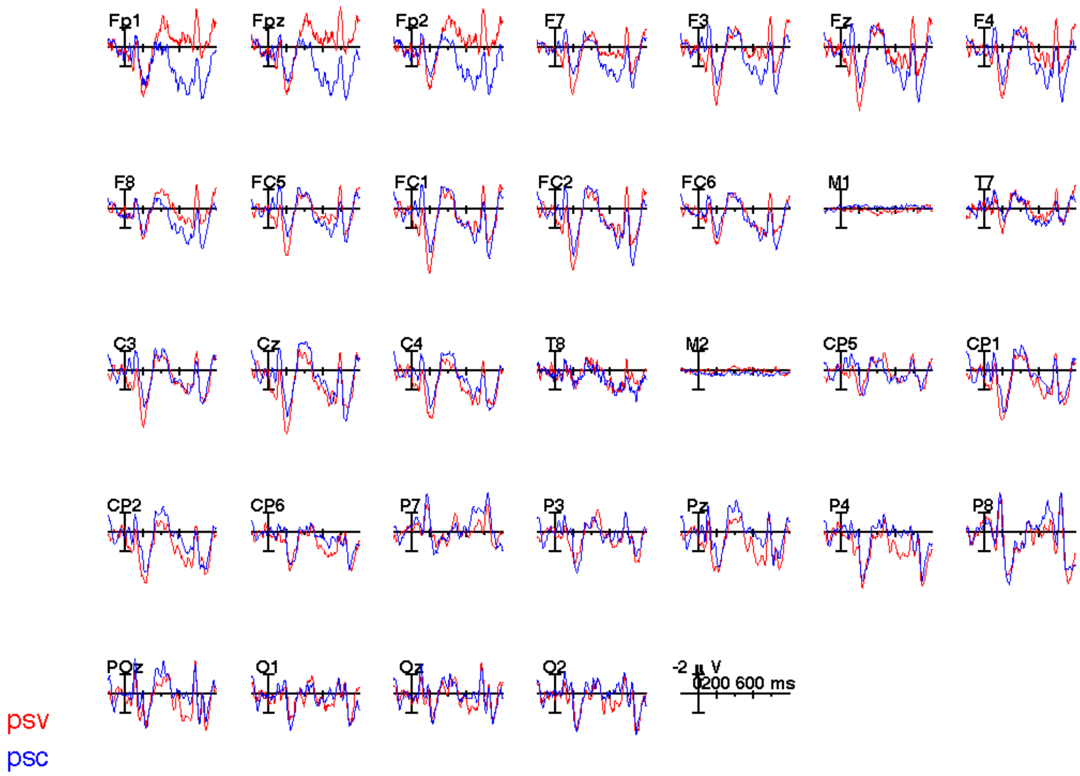
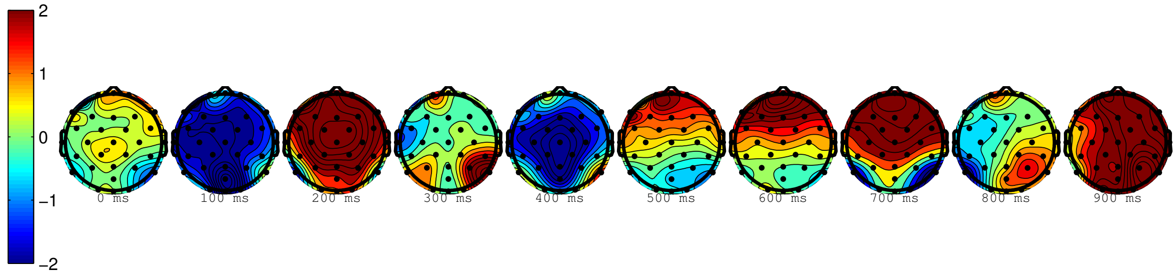
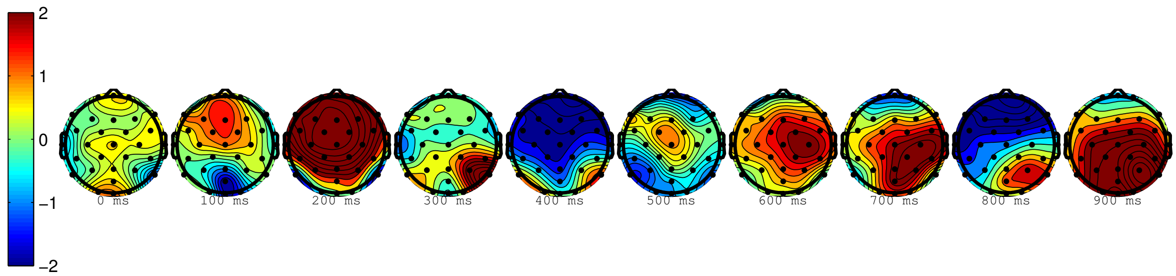


Figure A.165: Reanalysis with subset of subjects (13), Phrase Structure Violation: topoplots

Phrase Structure Control



Phrase Structure Violation



Difference plots

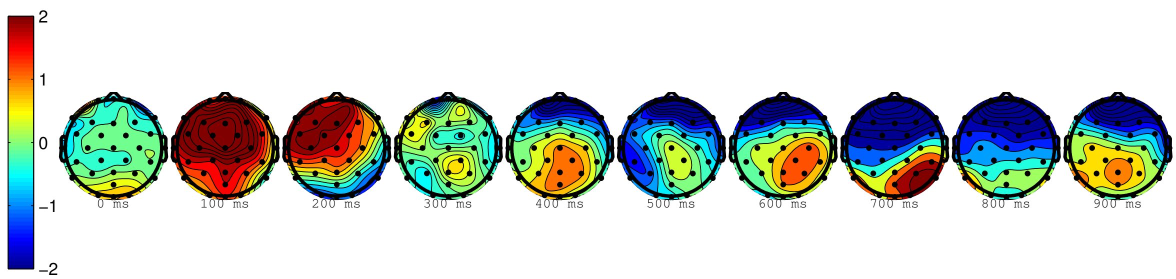


Figure A.166: Reanalysis with subset of subjects (13), Phrase Structure Violation: t_{max} permutation tests

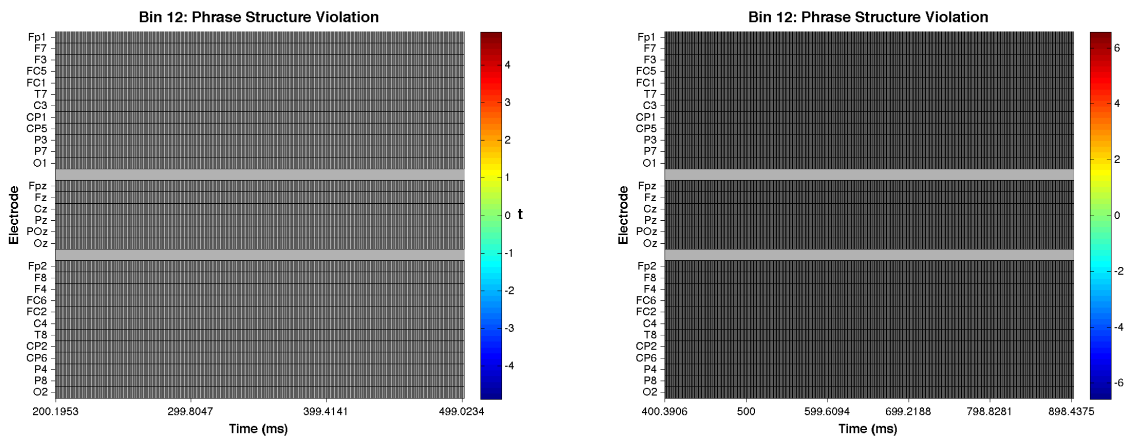
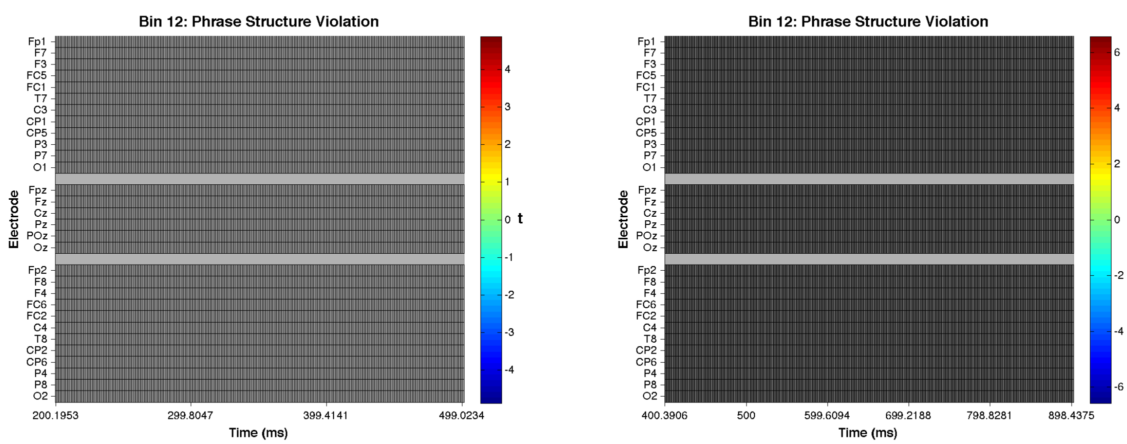


Figure A.167: Reanalysis with subset of subjects (13), Phrase Structure Violation: cluster mass permutation tests



TFRs

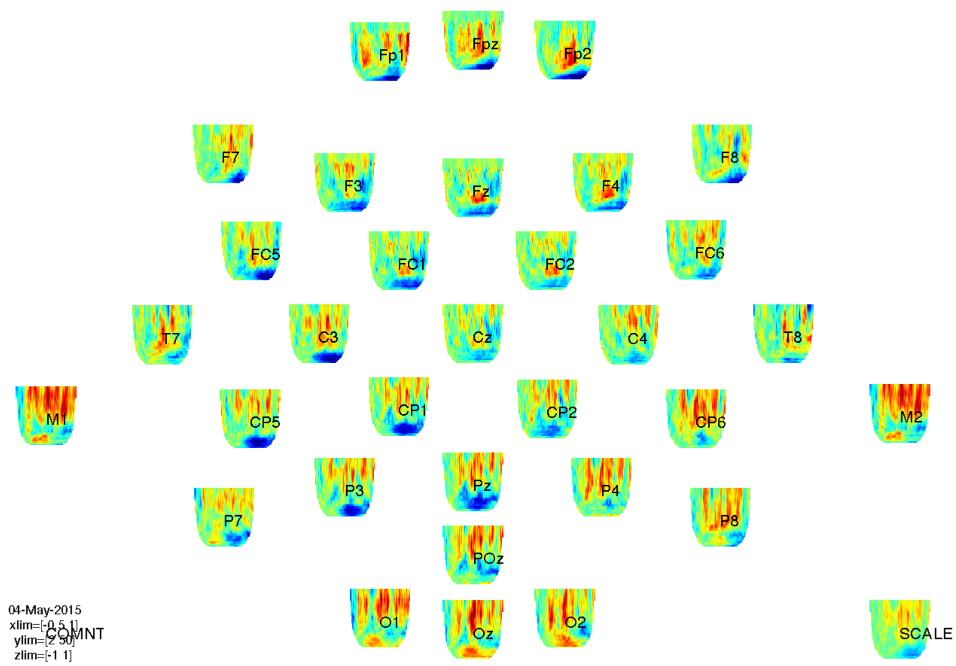


Figure A.168: Reanalysis with subset of subjects (13), Phrase Structure Violation: TFR

Figure A.169: Reanalysis with subset of subjects (13), Phrase Structure Violation: Theta band (4-7Hz) masked stats TFR

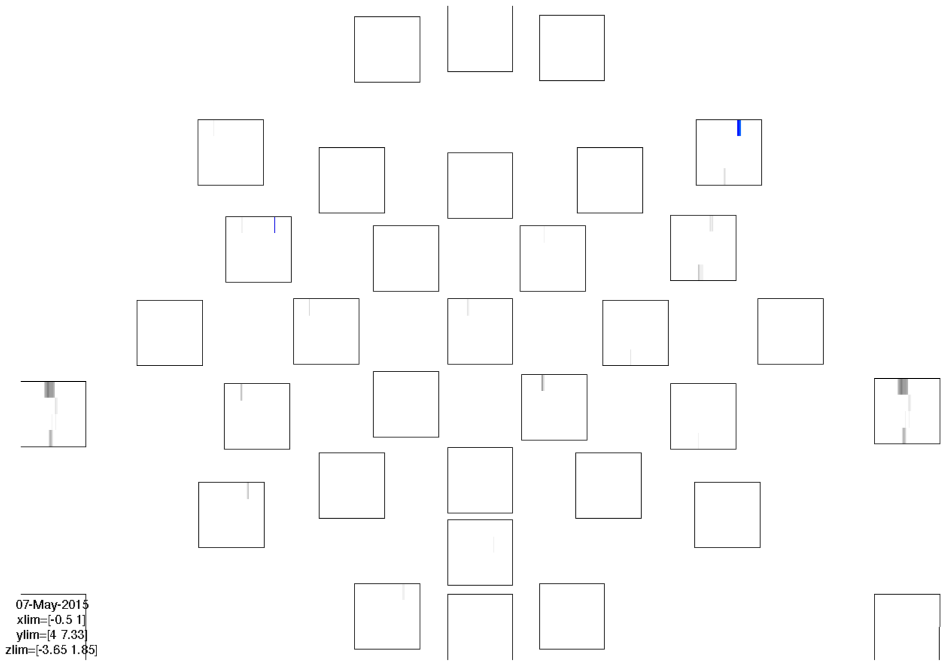


Figure A.170: Reanalysis with subset of subjects (13), Phrase Structure Violation: Theta band (4-7Hz) masked stats TFR, significant channels

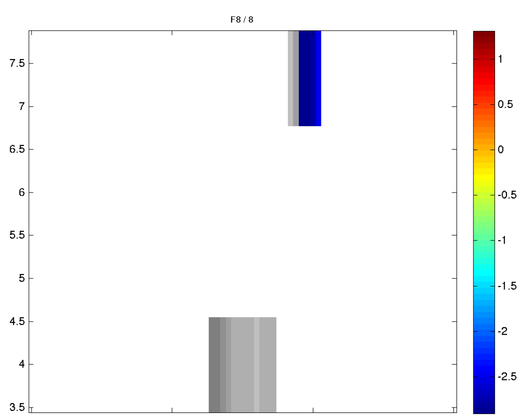


Figure A.171: Reanalysis with subset of subjects (13), Phrase Structure Violation: Alpha band (8-12Hz) masked stats TFR

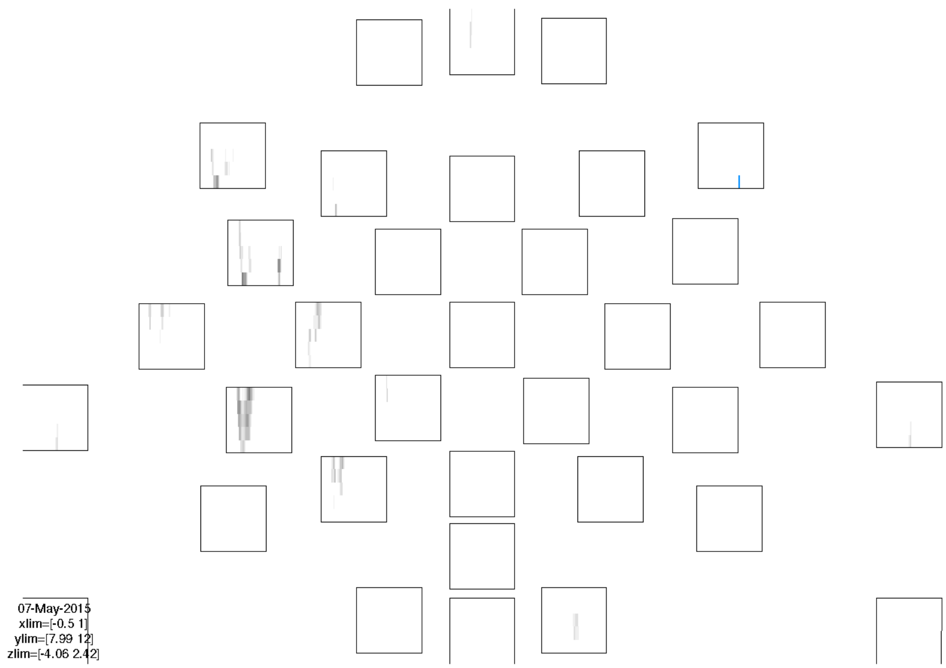


Figure A.172: Reanalysis with subset of subjects (13), Phrase Structure Violation: Alpha band (8-12Hz) masked stats TFR, significant channels

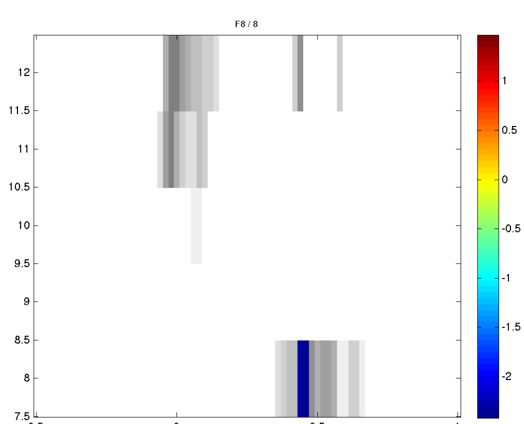


Figure A.173: Reanalysis with subset of subjects (13), Phrase Structure Violation: Lower Beta band (13-20Hz) masked stats TFR

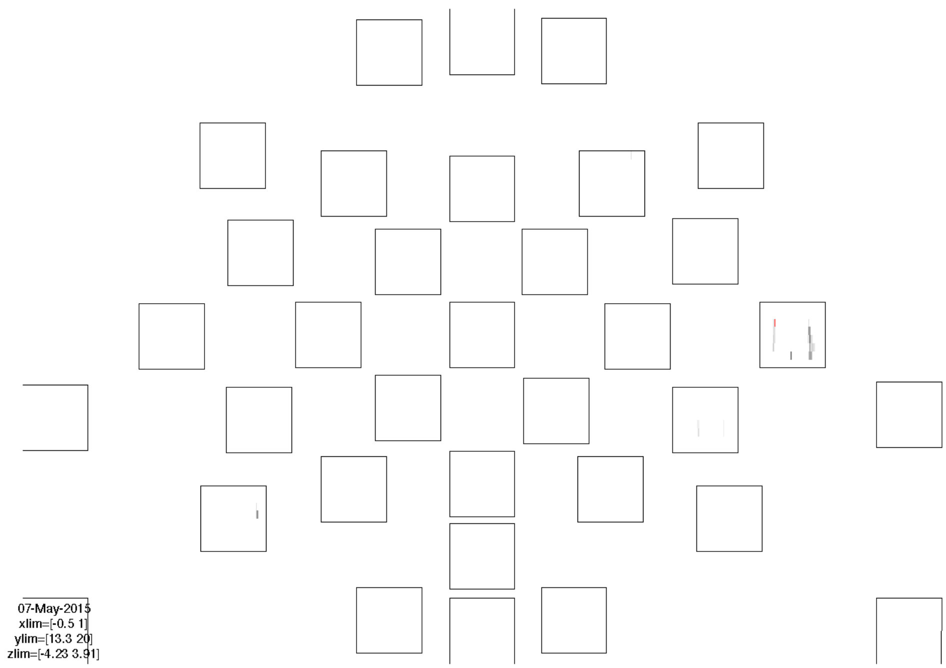


Figure A.174: Reanalysis with subset of subjects (13), Phrase Structure Violation: Lower Beta band (13-20Hz) masked stats TFR, significant channels

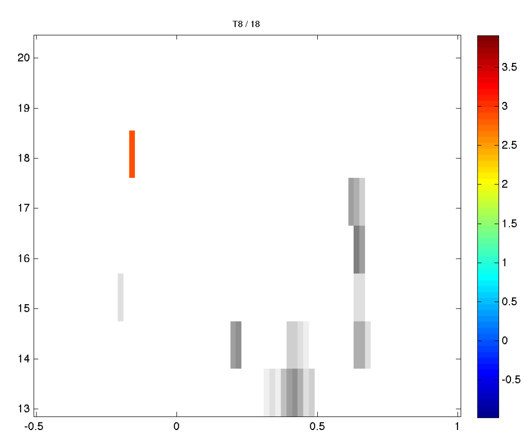


Figure A.175: Reanalysis with subset of subjects (13), Phrase Structure Violation: Upper Beta band (21-30Hz) masked stats TFR

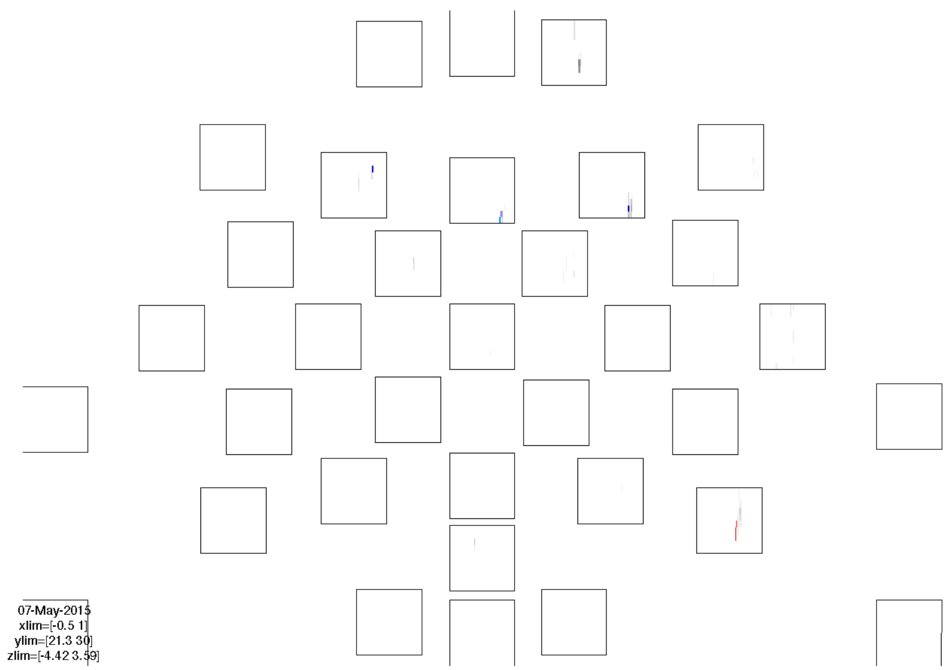


Figure A.176: Reanalysis with subset of subjects (13), Phrase Structure Violation: Upper Beta band (21-30Hz) masked stats TFR, significant channels

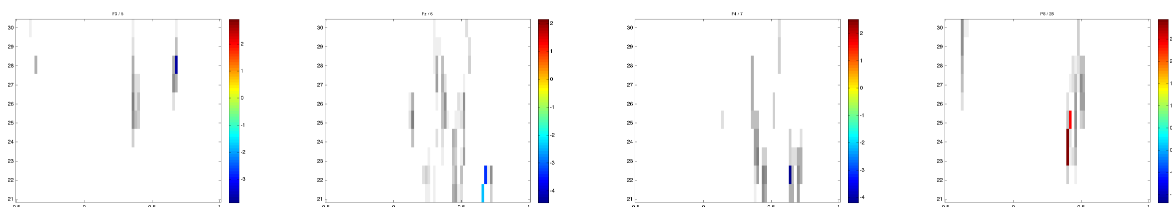


Figure A.177: Reanalysis with subset of subjects (13), Phrase Structure Violation: Gamma band (31-40Hz) masked stats TFR

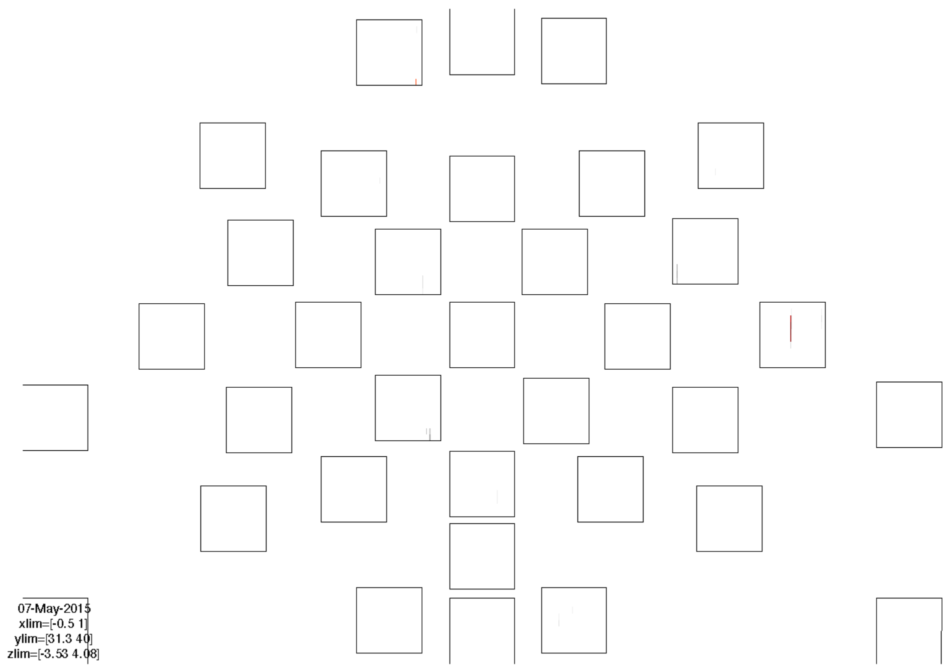


Figure A.178: Reanalysis with subset of subjects (13), Phrase Structure Violation: Gamma band (31-40Hz) masked stats TFR, significant channels