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Research Report

Understanding counterfactuals in discourse modulates ERP and oscillatory gamma rhythms in the EEG

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ABSTRACT

This study provides ERP and oscillatory dynamics data associated with the comprehension of narratives involving counterfactual events. Participants were given short stories describing an initial situation ("Marta wanted to plant flowers in her garden…."), followed by a critical sentence describing a new situation in either a factual ("Since she found a spade, she started to dig a hole") or counterfactual format ("If she had found a spade, she would have started to dig a hole"), and then a continuation sentence that was either related to the initial situation ("she bought a spade") or to the new one ("she planted roses"). The ERPs recorded for the continuation sentences related to the initial situation showed larger negativity after factuals than after counterfactuals, suggesting that the counterfactual's presupposition – the events did not occur – prevents updating the here-and-now of discourse. By contrast, continuation sentences related to the new situation elicited similar ERPs under both factual and counterfactual contexts, suggesting that counterfactuals also activate momentarily an alternative "as if" meaning. However, the reduction of gamma power following counterfactuals, suggests that the "as if" meaning is not integrated into the discourse, nor does it contribute to semantic unification processes.

1. Introduction

Let us suppose that you are reading a narrative, and you learn that the protagonist Mary is short of money and eager to navigate around the world. At a given point you read a counterfactual statement: "If she had bought that lottery ticket, she would have bought the yacht of her dreams". If you then read: "she approached the harbor and took pictures of a new yacht", this looks perfectly fine because the counterfactual events did not change the current Mary's situation (still short of money and just dreaming on yachts). Let us suppose that you read a different continuation of the story: "she approached the harbor and docked her new yacht". You may find this inconsistent because according to the counterfactual context you know that she does not have a yacht. However, counterfactual meaning is not so simple; according to some theories the counterfactual conveys a dual representation: the real situation (the protagonist did not buy the lottery ticket, nor did she buy a yacht), and the alternative situation (she bought the lottery ticket and also bought the yacht). So, one possibility is that when you read the above continuation sentence you do not find it so

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inconsistent because you also have momentarily represented the counterfactual situation "as if" it were real. This paper explores how the dual meaning of counterfactuals modulates the updating processes in discourse contexts like that.

The dual meaning of the counterfactual has been initially explored in the field of conditional reasoning (e.g., Byrne, 2002, 2005; Johnson-Laird and Byrne, 2002; Kahneman and Tversky, 1982; Thompson and Byrne, 2002). Most of these studies used offline methods in which participants first read a factual conditional (e.g., "If Mike went to Calgary, then Barbara went to Edmonton") or a counterfactual conditional (e.g., "If Mike had gone to Calgary, then Barbara would have gone to Edmonton"), and were then asked to choose from among several sentences those which were more consistent with or were implied by the conditional sentence's meaning. The results typically confirm that participants tend to exclusively choose a factual interpretation (p & q) for factual conditionals, but they choose both factual (p & q) and negation (not-p & not-q) for counterfactual conditionals.

Only recently have researchers in language comprehension paid attention to counterfactuals, exploring the temporal course of their dual meaning activation (De Vega and Urrutia, 2012; De Vega et al., 2007; Ferguson and Sanford, 2008; Stewart et al., 2009). For instance, De Vega et al. (2007) found that immediately after reading counterfactual events they remain accessible in memory exactly like in factual stories. However, counterfactuals do not change the protagonist's here-and-now because readers understand that counterfactual events did not happen. Consequently, the initial situation, preceding the counterfactual events in the narrative, remains more accessible in the counterfactual than in the factual version of the stories (De Vega et al., 2007, Experiment 2; De Vega and Urrutia, in press). In sum, it would seem that readers of counterfactual sentences activate a mental model of the presupposed situation (the implicit negation: not-p & not-q), which does not change here-and-now as well as, at least momentarily, an alternative mental model consisting of "undoing" the reality and contemplating its hypothetical consequences (p & q). Notice that the two conflicting meanings of counterfactuals play an important role, expressing the protagonist's mental states, such as her regret or relief (Byrne, 2002, 2005; Kahneman and Tversky, 1982; Thompson and Byrne, 2002), and thus contributing to some form of discourse updating.

In contrast with the dual meaning account of counterfactuals, Evans (2006) proposed that only one situation model for counterfactuals exists, corresponding to the conditional supposition "if p then q", and any conflicting factual information would be pragmatically irrelevant. Some reading studies, however, failed to support Evans' suppositional account, favoring instead the dual meaning proposal (Ferguson and Sanford, 2008; Stewart et al., 2009). For instance, Ferguson and Sanford (2008) used the eye-movement technique to demonstrate that, after reading a counterfactual sentence conflicting with real-world knowledge ("If cats were vegetarians they would be cheaper for owners to look after"), participants cannot avoid representing the real-world situation, in spite of its irrelevance for the conditional reasoning "if p then q". Thus, when participants received a continuation sentence consistent with the counterfactual premises but conflicting with their real-world knowledge ("Families could feed their cat a bowl of carrots"), they read it as slowly as when it was preceded by a factual context ("If cats are hungry they usually pester their owners until they get fed"). More recently, using the ERP technique, Nieuwland and Martin (2012) provided some support for the suppositional account. They found a larger N400 wave for false negated counterfactuals (e.g., "If NASA had not developed its Apollo Project, the first country to land on the moon would have been *America*") than for their true counterparts (e.g., "If NASA had not developed its Apollo Project, the first country to land on the moon would have been *Russia*"), suggesting that real-world knowledge does not disrupt counterfactual comprehension, and readers infer online the consequence of the counterfactual premise. However, the difference in the materials and the task demands among these studies prevent us from taking definite consequences on the subject.

In this study, participants' EEGs were recorded while they read target sentences embedded in counterfactual or factual narratives similar to those used by De Vega et al. (2007). Participants' understanding of the target sentences thus required that these sentences be interpreted within the whole discourse. The stories were written in four versions, with each differing in a critical sentence that was either factual or counterfactual, and in a continuation target sentence that was related either to the introductory events or to the immediately preceding context. An example of all four versions of a story is shown in Table 1. We were particularly interested in the EEG signatures associated with counterfactuals obtained *after* reading them, namely in the continuation sentences. At these loci we could check how updating processes were differently modulated by counterfactual and factual stories.

Our hypotheses focus on two different measures derived from the EEG analyses: the N400 and other components of the ERP, and the oscillatory dynamics (notably in the gamma frequency range) obtained from time–frequency analysis.

Table 1 – Example of an instrumental story in all four versions (both the translation into English and the original Spanish version are provided).

Initial situation:
Marta wanted to plant flowers in her garden, because it was quite neglected. The soil was hard and dry, and full of weeds
Critical sentence (new situation):
- Factual: Because she found a spade, she started to dig a hole
- Counterfactual: If she had found a spade, she would have started to dig a hole

Continuation sentence
- Related to initial situation: Marta *bought a spade* in / *the market* and used it the next day.
- Related to new situation: Marta *planted some roses* in / *the ground* and watered them abundantly.

[Marta quería plantar unas flores en su jardín, pues lo tenía bastante abandonado. La tierra estaba dura y seca, y llena de malezas.
Factual: Como tenía una pala, empezó por cavar un hoyo
Counterfactual: Si hubiera tenido una pala, hubiera empezado por cavar un hoyo.
Related to initial situation: Marta *compró una pala* en / *el mercado* y la usó al día siguiente.
Related to new situation: Marta *plantó unas rosas* en / *el suelo* y las regó en abundancia.]

The classical N400 consists of an increased negative wave peaking around 400 ms after the onset of words that violate the semantic expectations generated by preceding words in the sentence (Kutas and Hillyard, 1980, 1984). Especially interesting for the current study is the fact that the N400 is also sensitive to discourse-level semantic anomalies (Federmeier and Kutas, 1999; Hald et al., 2007; León et al., 2010; Nieuwland and Van Berkum, 2006; St. George et al., 1997; Van Berkum et al., 1999, 2003). For instance, Van Berkum et al. (2003) analyzed words, like *quick*, which were locally consistent in the sentence context (e.g. in "Jane told her brother that he was exceptionally quick"), but were made discourse-anomalous when the sentence was preceded by a previous narrative in which the brother's behavior could better be described as *slow*. The discourse-anomalous words elicited a typical N400 with a centro-parietal distribution. In this study we expect that the N400 will be sensitive to discourse-level updating processes in counterfactual and factual stories.

The second analysis performed on our data consists of time–frequency (TF) analysis of power changes. The typical ERP procedure of averaging segments of EEG time-locked to critical stimuli largely cancels out the EEG oscillations that could also provide functional information related to cognitive processing. Performing TF analysis of EEG power provides an empirical approach to oscillatory brain dynamics, and has shown to be informative on language comprehension processes. From a comprehensive review of the rapidly growing body of literature on TF analysis (Bastiaansen and Hagoort, 2006), a picture emerges in which different aspects of language comprehension systematically affect power and coherence estimates in different frequency ranges. Retrieval of word-level information is mostly accompanied by increased neuronal synchronization in the theta frequency range (4–7 Hz; Bastiaansen et al., 2005, 2008). Sentence-level syntactic binding (unification), in contrast, induces neuronal synchronization in the beta frequency band (12–30 Hz; Bastiaansen et al., 2010; Haarmann et al., 2002; Weiss et al., 2005).

Most relevant to our present purpose however, is the notion that there is a relationship between gamma-band neuronal synchronization and sentence-level semantic processing. For example, in one study (Hald et al., 2006), an increase in gamma power (around 40 Hz) was observed in response to a high-cloze critical word (CW) presented in a sentence context. This gamma increase was abolished when the CW was semantically anomalous. These results were replicated in a recent study (Rommers et al., submitted for publication), which additionally revealed that semantically anomalous CW's that were nevertheless semantically related to the expected, high-cloze CW, elicited an intermediate increase in gamma power. Further, using EEG coherence analysis, one study (reviewed in Weiss and Mueller, 2003) reported increased gamma-band coherence between left frontal and left temporal electrodes for a semantically correct CW compared to a semantically anomalous CW. In another study (Van Berkum et al., 2004) we observed a gamma power increase for referentially correct CW's, that disappeared when these CW's were referentially ambiguous, or did not have a proper referent. What all these findings have in common, are an increase in gamma (~40 Hz) power or coherence when semantic unification can be routinely performed, and a disruption of this gamma increase when semantic anomalies are encountered. Based on these findings, we have proposed (Bastiaansen and Hagoort, 2006; Varela et al., 2001) that gamma-band neuronal synchronization is related to normal, ongoing semantic unification operations. Two recent studies, in which gamma power time courses were computed across entire sentences, further support this proposition. In the first (Peña and Melloni, 2012), gamma power increases were observed only when Spanish or Italian monolinguals listened to sentences in their own language, not when they listened to sentences spoken in a phonologically related or an unrelated language. Note however that in this study, gamma power changes were observed in a higher gamma frequency range (around 70 Hz) than in the previously mentioned studies. In the second study (Bastiaansen and Hagoort, 2010) larger gamma power was observed across semantically congruent sentences compared to sentences that were syntactically correct, but semantically anomalous (so-called syntactic prose). Together, the existing data support the notion that gamma oscillations are markers of semantic unification processes. That is, gamma oscillations become more prominent during the process of assembling words into larger structures such as the sentence and the current discourse. We consider that updating is a kind of (semantic) unification process occurring in language, beyond the level of the sentence. Both updating and unification involve on-line integration of different sources of semantic information. Consequently, in this study we expect a reduction of oscillatory brain responses in the gamma frequency range for the target continuation sentence when it is inconsistent with the preceding factual or counterfactual context, because of the disruption of neural processes underlying the ordinary updating/semantic integration processes.

The EEG analyses were time-locked to words at two different loci placed in the continuation sentence (shown in bold in Table 1), and provide a view of the discourse-level updating processes associated with factual and counterfactual meanings. The rationale of analyzing ERP and power changes in these continuation sentences is as follows: after listening to a critical factual sentence (e.g. "because she found a spade…"), participants update the protagonist's here-and-now, and the continuation sentence related to the initial situation (e.g. "bought a spade in the market") becomes inconsistent. By contrast, after listening to a counterfactual sentence ("if she had found a spade…."), participants know from the counterfactual presupposition that the referred events (finding a spade and digging a hole) did not happen, and thus the continuation sentence related to the initial situation makes perfect sense. Therefore, we expected that sentences related to the initial situation would produce larger negative waves (e.g. N400) and smaller gamma power after a factual sentence than after a counterfactual sentence. Concerning continuation sentences related to a new situation (e.g. "planted some roses"), they would be appropriate after factuals because they contribute to the normal updating of the protagonist's here-and-now. After listening to counterfactuals, one possibility is that sentences related to a new situation become inconsistent because, given the counterfactual presupposition, the antecedent events did not happen. If so, we could expect larger ERP negative waves and reducing TF gamma power in comparison with factual contexts. However, if the dual meaning proposal is true sentences related to a new situation could also be momentarily valid, because the

counterfactual events would also be activated. In such case, we should not expect differences between factual and counterfactual contexts ERP waves or TF gamma power. The separate analysis of the third locus will provide a better resolution of the temporal course of meaning in the continuation sentences. According to some authors (e.g. Just and Carpenter, 1980; Rayner et al., 2000), the end of the sentence has a special status and it could be possible that specific wrap-up processing events, differing for factual and counterfactual stories, take place at this point.

The counterfactual stories employed in this study involved two types of scenarios in which a protagonist's goal was not achieved, either because his/her displacement to another place did not take place (spatial stories), or because the critical instrument to achieve the goal was not available (instrumental stories). By contrast, the factual version of the stories, used as a contrast condition, involved performing the displacement or obtaining the instrument necessary to achieve the corresponding goal. The example in Table 1 is an instrumental story, whereas an example of a spatial story can be found in Appendix A. Notice that the counterfactual alternatives given in the stories are close to the facts. Like most counterfactuals spontaneously produced in real-world situations, they involve just a slight change in the conditional event rather than a bizarre or unrealistic change (Byrne, 2005; Kahneman and Tversky, 1982; Roese, 2005). We do not have any specific hypothesis about spatial and instrumental stories. The two contents, however, were counterbalanced, which allows for them to be analyzed separately, and thus to explore possible "content effects". In principle, we can expect that the counterfactual format produces the same effects with both instrumental and spatial content. Otherwise, we might conclude that processing of counterfactuals does not exclusively depend on their linguistic form (e.g. the presence of the conditional "if", or of verbs in the subjunctive mood), but is modulated by the particular content.

2. Results

2.1. *First locus: verbal phrase in the continuation sentence*

2.1.1. *ERP*

The first locus corresponds to the three-word verbal phrase (verb–determiner–noun) of the continuation sentence (see Table 2). Fig. 1 shows the grand average waveforms for instrumental stories elicited for the initial-related continuation sentence ("bought a spade", in Table 1) in the fronto-central and the centro-parietal regions, and Fig. 2 illustrates the recording for the new-related continuation sentence ("planted some roses", in Table 1) in the same set of electrodes and stories. Figs. 3 and 4 are the equivalents for spatial stories of Figs. 1 and 2, respectively. A visual inspection of Figs. 1–4 suggests that most effects seem to be associated with instrumental stories and initial-related sentences (Fig. 1), in which there is a larger negative wave for factual than for counterfactual contexts, which is most pronounced at fronto-central sites. This negativity starts immediately after the verb (N100/P200 component), and continues throughout the whole phrase. By contrast, the new-related sentences produce similar ERP waveforms for both factual and counterfactual contexts. Spatial stories apparently do not show any sensitivity to contextual factors.

As mentioned above, two epochs produced significant effects at this locus: an early epoch elicited by the verb (115–235 ms) and a later epoch (1400–1650 ms) corresponding to 300–450 ms after noun onset.

2.1.1.1. 115–235 ms after verb onset. Despite the clear differences in ERP waveforms between spatial and instrumental stories at this temporal window (Figs. 1–4), the three-way Context × Continuation × Content interaction failed to reach significance. However, in a parallel analysis, in which we replaced the factors Region and Hemisphere by a single factor, Electrode, consisting of all the 51 electrodes, we did find such a three-way interaction ($F(1, 29) = 4.99$, $MSe = 121.76$, $p < .033$). Therefore, separate analyses (using Region and Hemisphere again as factors) were performed for instrumental and spatial stories. As expected, for instrumental stories, a three-way Context × Continuation × Region interaction ($F(1, 29) = 9.27$, $MSe = 288.35$, $p < .005$) was found, whereas for spatial stories, no such effect was observed. Simple-effects tests for instrumental stories indicated that the Context × Continuation interaction was significant for the fronto-central region ($F(1, 29) = 6.37$, $MSe = 615.93$, $p < .017$), but not for the centro-parietal region ($F(1, 29) < 1$). This interaction reflects the fact that for instrumental stories, there was a reduction of the positive deflection in sentences referring to the initial situation when they were preceded by a factual rather than a counterfactual context. This reduced positivity is evident throughout the entire recording interval (Fig. 1). By contrast,

Table 2 – Continuation sentences: means and standard deviations (in parenthesis) of lexical frequency [a] and length for the content words in the first and the second loci.

	First locus: verb		First locus: noun		Second locus: noun	
	Length	Frequency	Length	Frequency	Length	Frequency
Spatial						
Initial-related	5.8 (1.6)	58 (76)	6 (1.6)	71(115)	5.8 (1.4)	105 (197)
New-related	5.8 (1.5)	58 (81)	6(1.5)	61(107)	5.7 (1.4)	90 (131)
Instrumental						
Initial-related	5.5 (1.4)	46 (69)	5.8 (1.3)	41(78)	5.8 (1.4)	63 (113)
New-related	5.5 (1.3)	46 (60)	5.9 (1.4)	42(76)	5.7 (1.5)	64 (92)

[a] Lexical frequency was obtained in the Davis and Perea (2005) dictionary.

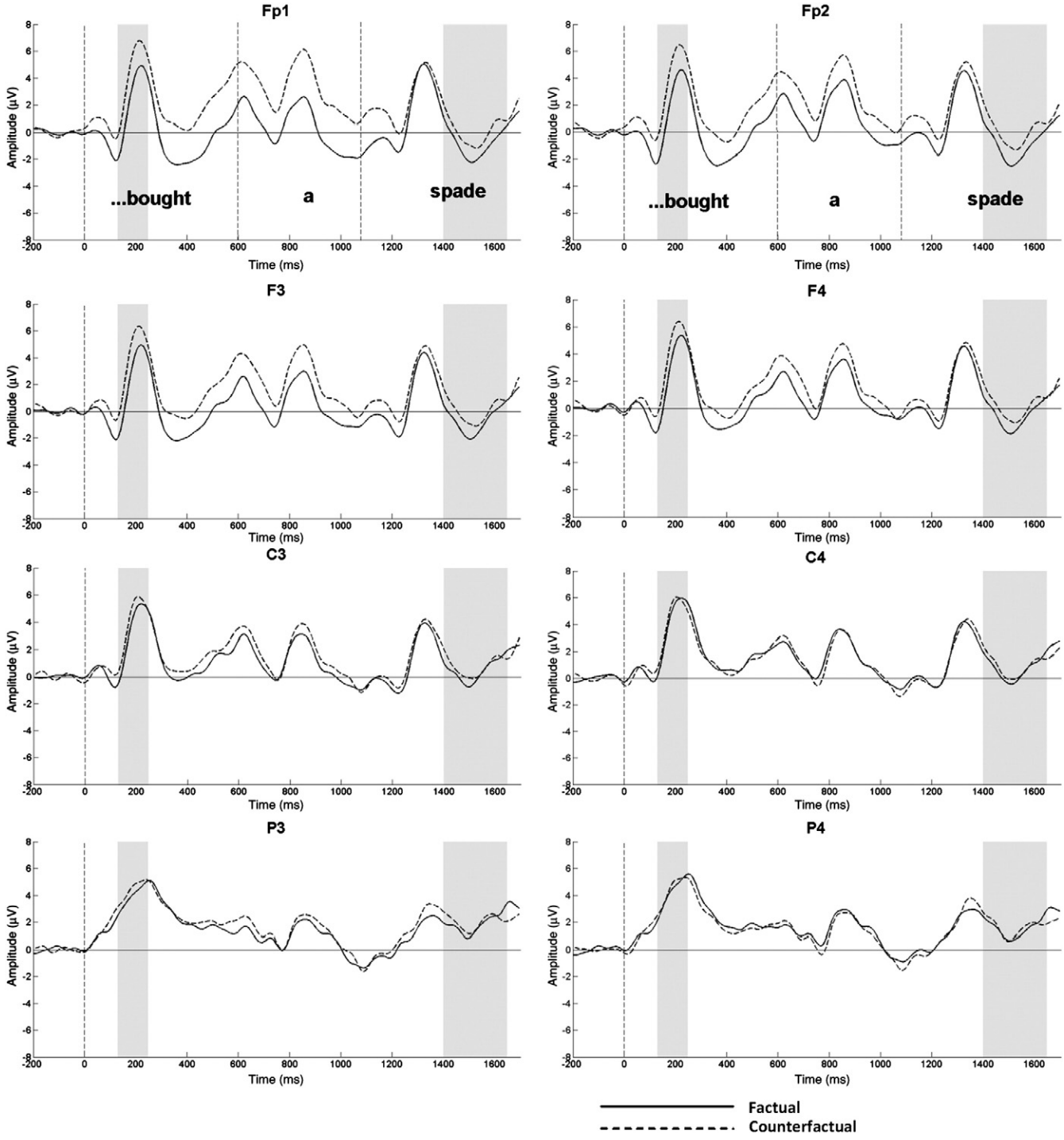

Fig. 1 – Initial-related continuation phrase ("…bought a spade") in instrumental stories. ERP grand average for factual and counterfactual stories in a selection of fronto-central (Fp1, Fp2, F3, and F4) and centro-parietal (C3, C4, P3 and P4) electrodes. Factual sentences produced a more negative wave with a fronto-central distribution.

no differences between factual and counterfactual contexts were observed for the same instrumental stories in sentences referring to the new situation (Fig. 2).

2.1.1.2. 1400–1650 ms after verb onset (300–450 ms after the noun onset). A four-way Context × Content × Continuation × Region interaction was found ($F(1, 29) = 4.00$, $MSe = 85.39$, $p < .05$). Simple effects tests showed that the Context × Continuation × Region interaction was significant for instrumental stories ($F(1, 29) = 7.16$, $MSe = 114.86$, $p < .012$), but not for spatial stories ($F(1, 29) < 1$). Further breaking down this interaction, a Context × Continuation interaction was obtained at the fronto-central region ($F(1, 29) = 5.17$, $MSe = 246.400$, $p < .031$), but not at the centro-parietal region ($F(1, 29) < 1$). This effect reveals that reading

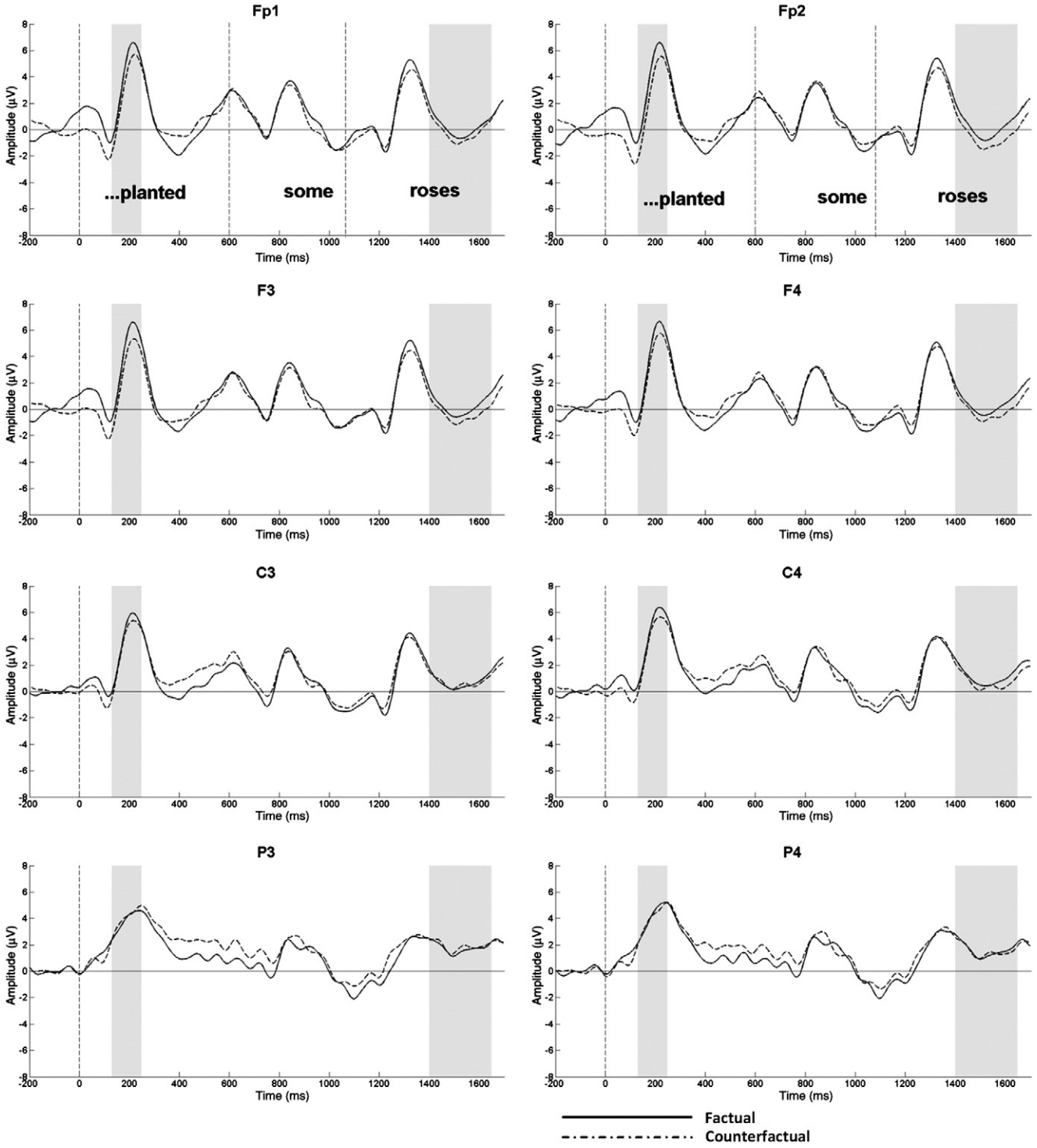

Fig. 2 – New-related continuation phrase ("…planted some roses") in instrumental stories. ERP grand average for factual and counterfactual stories in a selection of fronto-central (Fp1, Fp2, F3, and F4) and centro-parietal (C3, C4, P3 and P4) electrodes.

initial-related sentences elicited a larger negativity after listening to a factual than after listening to counterfactual context (see Fig. 1). By contrast, reading new-related sentences did not produce any significant difference between factual and counterfactual contexts (see Fig. 2). In spatial texts, the only significant result was a main effect of Continuation in the same frontal electrodes ($F(1, 29) = 4.32$, $MSe = 46.23$, $p < .045$). Specifically, a larger negativity was observed for initial-related than for new-related continuations in both factual and counterfactual contexts, indicating the cost of retrieving information related to the initial situation regardless of the particular context.

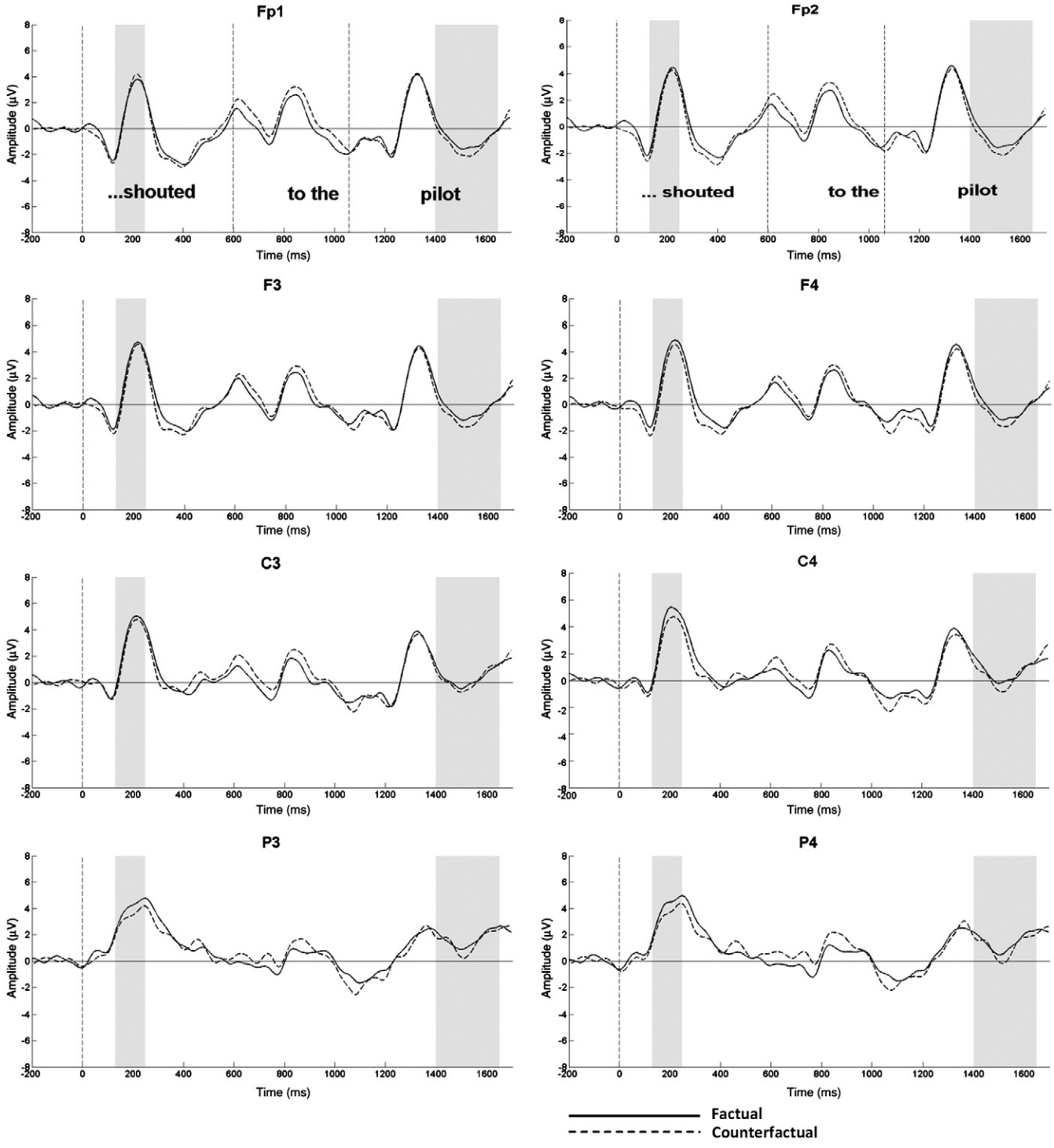

Fig. 3 – Initial-related continuation phrase ("...shouted to the pilot") in spatial stories. ERP grand average for factual and counterfactual stories in a selection of fronto-central (Fp1, Fp2, F3, and F4) and centro-parietal (C3, C4, P3 and P4) electrodes.

Notice that, unlike the typical centro-parietal N400 distribution, the present negativity is fronto-central. Similar frontal N400-like effects have been reported for ambiguous words in comparison to non-ambiguous words processed in resolutory sentence contexts (Hagoort and Brown, 1994). Counterfactuals, like ambiguous words, also involve alternative meanings; therefore the frontal distribution may indicate more cognitive demands associated with the processing of multiple meanings.

2.1.2. *TF analysis*

None interaction was significant in the analyses. The only statistical effects found was a significant cluster ($p=0.03$) for the full set of stories (spatial and instrumental together),

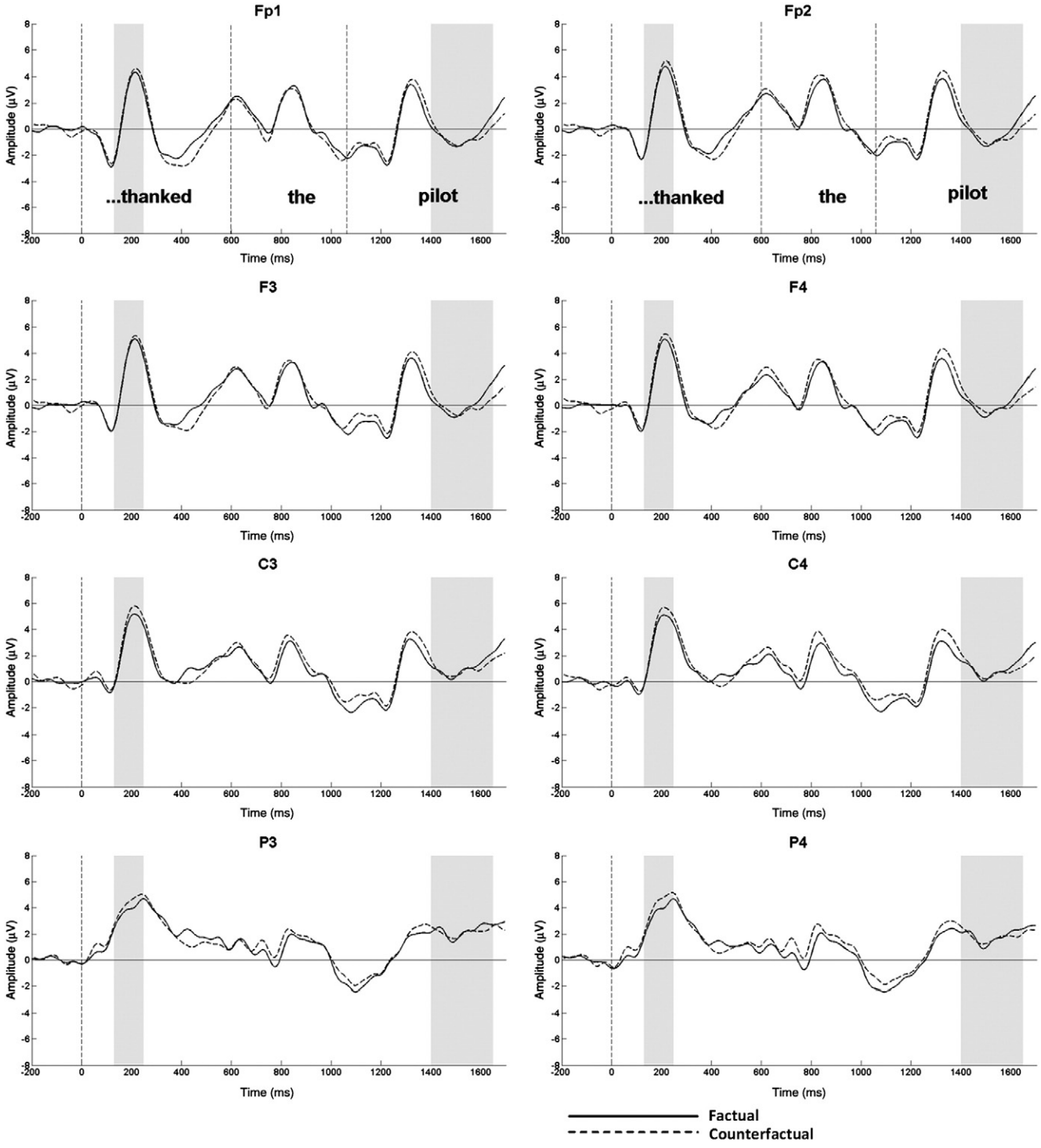

Fig. 4 – New-related continuation phrase ("…thanked the pilot") in spatial stories. ERP grand average for factual and counterfactual stories in a selection of fronto-central (Fp1, Fp2, F3, and F4) and centro-parietal (C3, C4, P3 and P4) electrodes.

indicating a larger power in the gamma frequency range of 80–90 Hz for new-related continuations and following the factual rather than the counterfactual context. This effect was largest at left frontal electrodes in the 300–800 ms time window after the verb onset (Fig. 5). Note that a visual inspection of Fig. 5 suggests the presence of a strong increase in gamma power for the factual contexts, around 40 Hz. However, the resulting cluster did not even come close to reaching significance ($p=0.48$), indicating that this apparent effect is not consistently present across subjects.

2.2. *Second locus: final words in the continuation sentence*

2.2.1. *ERP*

Fig. 6 displays the waveforms elicited by the final words averaged for the two kinds of continuation sentences ("the

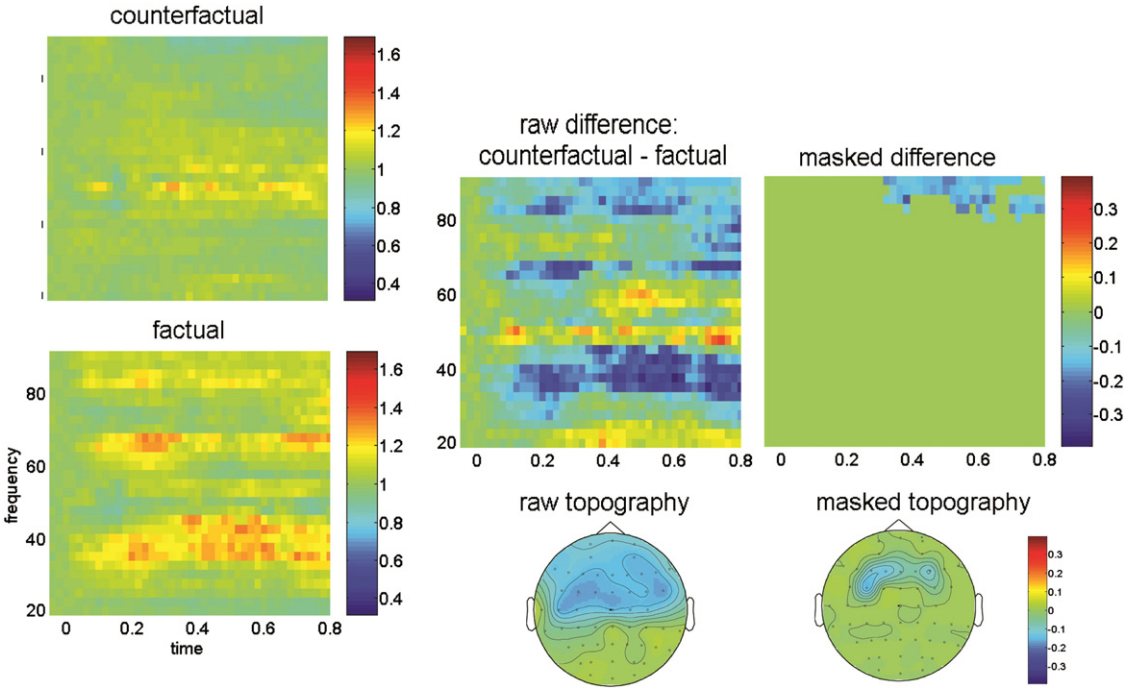

Fig. 5 – New-related continuation phrase ("…thanked the pilot") averaged for all the stories. Gamma power was significantly larger at frontal electrodes after factual contexts than after counterfactual contexts. Time–frequency representations are shown for channel FC3. Scalp topographies are given in a time–frequency interval from 300 to 800 ms post-stimulus, and from 80 to 90 Hz. See Fig. 2 legend for further details.

ground" and "the market" in Table 1). Content did not interact with the other variables; indicating that instrumental or spatial stories do not modulate the effects observed in final words. By contrast, a larger N400-like for the counterfactual than for the factual contexts can be observed, and this was confirmed by the significant main effects of Context in the 350–600 ms window ($F(1, 29)=5.84$, $MSe=527.17$, $p<.02$). There was also a main effect of Continuation ($F(1, 29)=8.90$, $MSe=1991.21$, $p<.0006$), which was qualified by Region ($F(1, 29)=7.06$, $MSe=456.13$, $p<.01$). Specifically, initial-related continuation sentences elicited a more negative wave than new-related continuation sentences, especially in the fronto-central region.

2.2.2. *TF analysis*

Again, content did not interact with the other variables, indicating that instrumental and spatial stories do not modulate differentially gamma rhythms at this locus. A visual inspection of Fig. 7 shows that, at the end of new-related sentences, a larger gamma power is recorded after a factual than after a counterfactual context. The statistical analyses confirmed a significant cluster ($p=0.04$) between 300 and 700 ms after the word onset, with a frequency range of 30–40 Hz and a right-dominant, parietal distribution. The increase in gamma power after a factual rather than a counterfactual context confirms the trend observed in the preceding words of the continuation sentences (first locus). Notice, however, that the TF pattern found here differs from the previous ones in frequency range (in that it is low gamma rather than high gamma) as well as in scalp distribution (in that it is parietal rather than frontal).

3. Discussion

In this study, we examined how brain activity is sensitive to the meanings of counterfactuals embedded in stories. Specific words following counterfactual contexts were compared with the same words in factual contexts. To obtain a complete picture of the course of the processing of meaning over time in our study, we analyzed the EEGs recorded at two different loci following the factual/counterfactual manipulation, as illustrated in Table 1: (1) the medial position words (verbal phrase) of the continuation sentences either in the initial-related ("bought a spade") or in the new-related version ("planted some roses"), and (2) the final words of these continuation sentences (either "the market" or "the ground"). These loci provide information on how updating or unification processes take place in sentences following factual or counterfactual contexts.

The study found differential ERP and TF components for counterfactuals when they were compared with factuals. First, the initial-related continuation sentences ("bought a spade") elicited more negativity in factual than in counterfactual contexts. Second, new-related continuation sentences ("planted some roses") elicited similar ERPs in both factual and counterfactual contexts, although gamma power reduction was observed in counterfactuals. Finally, the last words of the continuation sentences ("the market" or "the ground") produced a more negative wave and a gamma power reduction in counterfactuals. In this study, many ERP effects had a fronto-central distribution, which in some cases coincided with the distribution of the gamma power effects. However, most of the ERP effects were constrained to instrumental

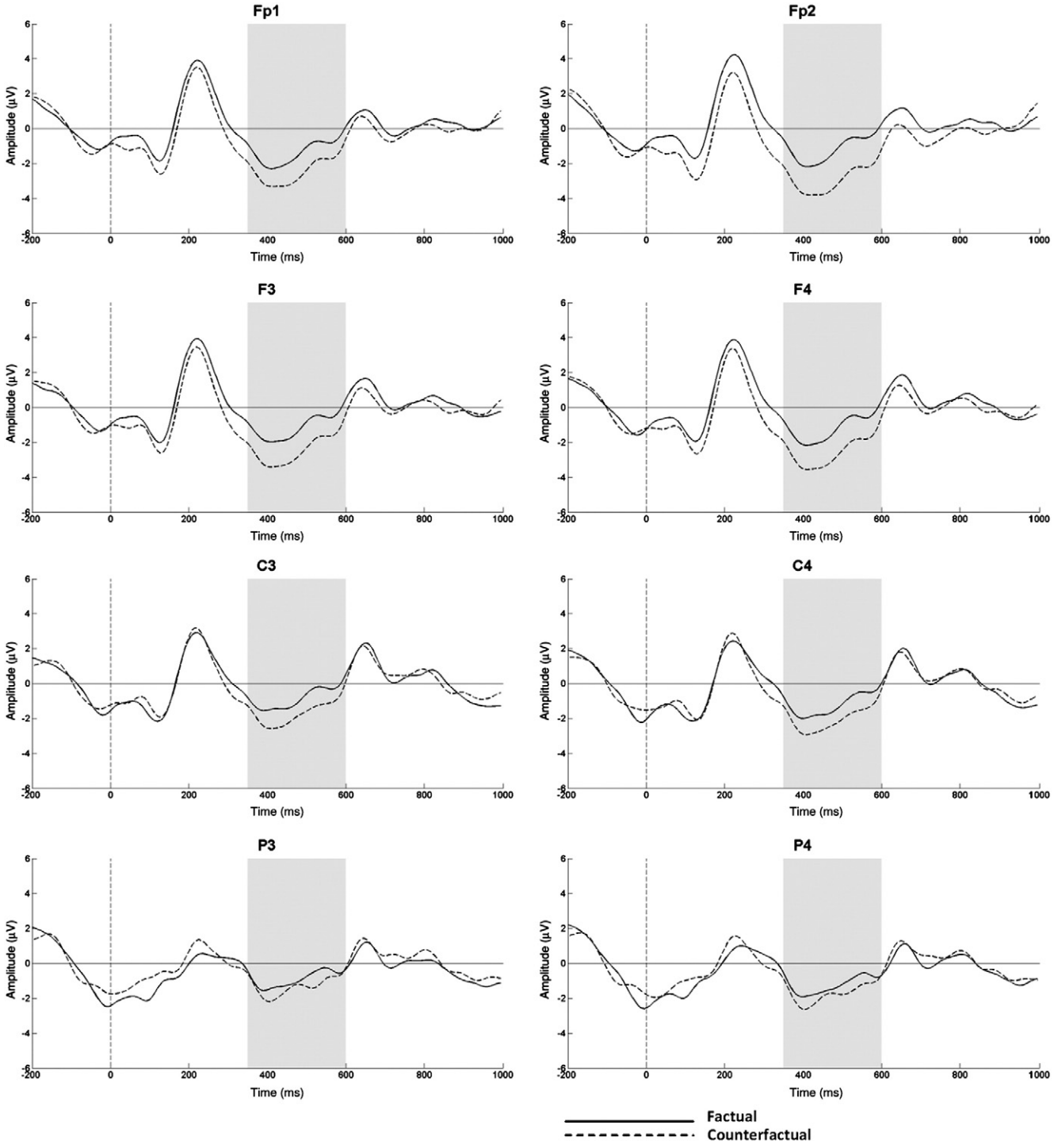

Fig. 6 – Last words of the continuation sentence averaged for all the stories. ERP grand average for factual and counterfactual stories in a selection of fronto-central (Fp1, Fp2, F3, and F4) and centro-parietal (C3, C4, P3 and P4) electrodes.

stories, whereas the gamma activity showed general sensibility for counterfactuals in both spatial and instrumental stories.

3.1. *Counterfactual meaning at the discourse level*

Some ERP studies show that discourse-level updating is a continuous process occurring throughout the whole sentence, without any special "wrap-up" episode at the sentence's last word (e.g. Van Berkum et al., 1999, 2003). The complex semantics of counterfactuals also induces a continuous updating throughout the ensuing sentence, which is most remarkable in the medial words of the continuation sentence (the first locus in this study). The Context×Continuation interaction obtained in the ERPs for instrumental stories

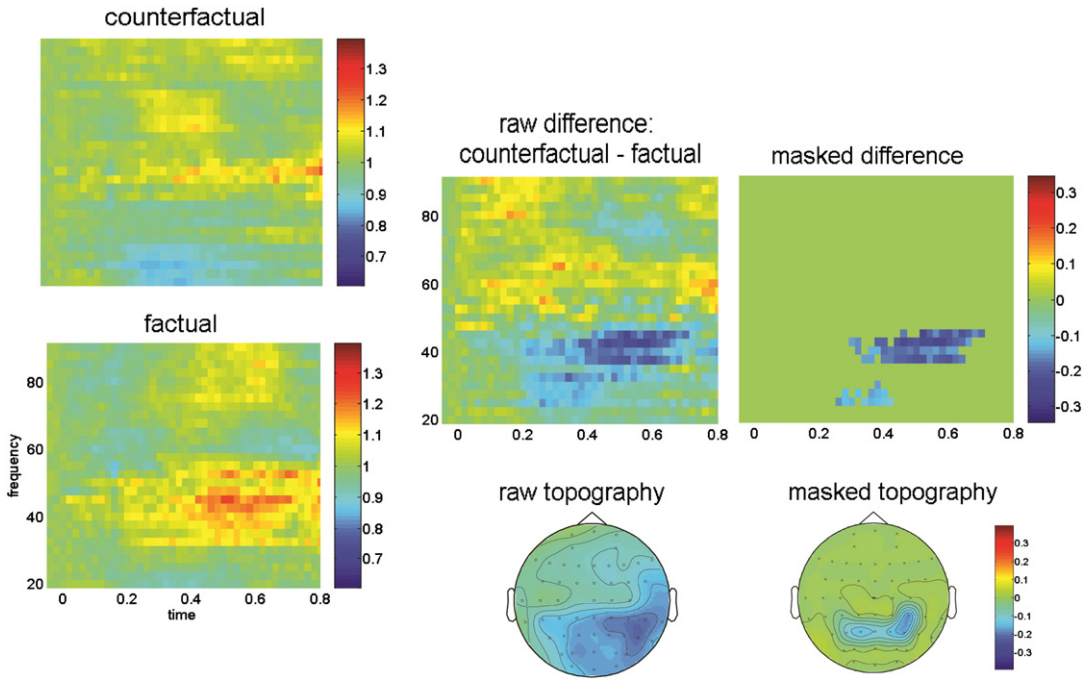

Fig. 7 – Last words of the new-related continuation sentences averaged for all the stories. Gamma oscillatory power elicited by the final word of new-related continuation sentences was significantly larger at parietal electrodes after factual contexts than after counterfactual contexts. Time–frequency representations are shown for channel P4. Scalp topographies are given in a time–frequency interval from 300 to 700 ms post-stimulus, and from 35 to 45 Hz. See Fig. 2 legend for further details.

demonstrates that updating processes differ between factual and counterfactual sentences. Specifically, after a counterfactual context, the initial-related continuation sentences ("bought a spade") were processed as semantically appropriate, as illustrated by the reduction of ERP negativity throughout the whole phrase in comparison with the same words preceded by a factual context. This means that the presupposition involved in counterfactuals (the implicit double negation: "not p & not q") renders consistent a continuation related to the initial scenario. This is exactly what would be expected because counterfactuals do not change the protagonist's here-and-now, and thus the previous factual situation is still valid. By contrast, after processing a factual context the "here and now" in the narrative situation changes (De Vega and Urrutia, 2012; De Vega et al., 2007; Zwaan and Madden, 2004), and the initial factual information becomes outdated and less accessible in the reader's memory. The negative ERP deflection in initial-related continuation sentences following a factual context would be compatible with such updating scenario.

The complete picture of counterfactual meaning is more complex, as the ERPs and TF data measured for medial words in new-related continuation sentences ("planted some roses") suggest. In this case, there was no difference in the ERPs after listening to factual and counterfactual contexts, suggesting that, in addition to the presupposed meaning, the alternative "as if" meaning of counterfactuals ("p & q") was also momentarily activated. However, a decrease in gamma power detected for counterfactuals indicates that the "p & q" representation, although activated, does not contribute to discourse-level unification or updating.

The early semantic effects obtained in the P200 component of the verb could be ascribed to an anticipatory effect. Let us recall the form of presentation of the materials used in the study. After listening to the factual or counterfactual context, participants received a continuation sentence starting with the protagonist's name presented auditorily with a suspended intonation (e.g. Marta…) followed by a verb and the remaining words visually. Consequently, it is to be expected that after hearing the protagonist's name, participants would generate a strong expectation for the verb, and thus inconsistent verbs following a factual context may have had an early influence 200 ms after verb onset. Similar anticipatory effects with impact on early ERP components have been reported elsewhere (e.g. León et al., 2010; Van Berkum et al., 2005).

The global context effect observed at the end of the sentence in the N400 component indicates that the previous counterfactual context still induced additional cognitive cost at the end of both initial-related and new-related sentences. Notice that, the contextual effect observed at this locus, although genuine could be mixed with the wrap-up processes occurring at the end of sentence. The TF data again qualifies the ERP results, because a reduction of gamma power in counterfactuals was observed only for new-related sentences (in both spatial and instrumental stories), confirming the general trend observed in the previous locus. This gamma effect suggests that at the end of the continuation sentence, the alternative "as if" meaning is not integrated, nor does it contribute to semantic unification. However, unlike in the previous locus, the distribution of this gamma effect was parietal rather than frontal, and located at a different frequency band, as we will comment below.

3.2. *Content effects*

The content of the stories (spatial or instrumental) modulates the effects of counterfactuals vs. factual context. Whereas the effects of context on gamma activity were similar for both spatial and instrumental stories, the most important contextual effects on ERPs were only significant for instrumental stories. We can rule out lexical factors to explain these differences, because they were controlled across stories. Concerning the plausibility of continuations, participants in the normative study (see method) judged more plausible initial-related continuations in counterfactual contexts than in factual contexts, and judged more plausible new-related continuations in factual contexts than in counterfactual contexts. This pattern was obtained both in spatial and instrumental stories alike, and even it was more extreme for spatial stories. Therefore, the metacognitive judgments of plausibility could not explain the content modulation of the results. Beyond plausibility the continuations in spatial and instrumental stories may differ in other aspects. Thus, instrumental stories describe more concrete, temporally constrained and causally connected events than spatial stories. Instrumental stories typically involve simple manual actions unfolding over a small temporal scale (of a few minutes), whereas spatial stories describe complex events extended in time (hours or days). Our hypothesis is that the small temporal scale and concreteness in instrumental stories makes more conspicuous the semantic anomaly of initial-related continuations in factuals. By contrast, the temporal features of spatial stories allow the reader to consider initial-related continuations as being discontinuous with the preceding factual events, and therefore acceptable as new events in another temporal slot.

Let us consider the counterfactuals of the spatial and instrumental examples (presented in Appendix A and Table 1, respectively). In the instrumental story, the events seem to occur over the course of a few minutes in a garden scenario, and thus the new-related continuation sounds odd (planting roses in the ground despite the fact that Marta didn't find the spade). By contrast, in the spatial story, the events are of long duration (3 days of navigation and probably hours of helicopter searching), and in such long events, implicit temporal breaks seem quite probable. To test this hunch, we ran a normative study, using a sample of 20 spatial and 20 instrumental stories in their consistent factual version. Participants estimated how long two time breaks in each story were: the first between the initial event and the critical event, and the second between the critical event and the continuation event. As expected, temporal discontinuities were significantly larger ($F(1, 38) = 5.37$, $p < .026$) in spatial stories (about 45 min) than in instrumental stories (less than 1 min). From the above argument, we can derive an important conclusion: some of the ERP effects associated with counterfactuals are not exclusively due to the grammatical format (e.g. conditional word + subjunctive mood), but rather depend on the degree to which readers can infer pragmatic scenarios which are compatible with both meanings of the story. A similar argument was proposed by Nieuwland and Martin (2012), who consider that counterfactual processing is strongly modulated by contextual constraints, which either enhance or reduce the relevance of real-world knowledge. Thus, dual meaning effects (including updating modulation) may depend on how much semantically constrained the counterfactual stories are. In this study instrumental stories are temporally constrained and show dual meaning effects both in the ERP and the TF analyses, whereas spatial stories are less constrained and their dual meaning effects are weaker in the ERP, but still visible in the dynamic oscillatory rhythms of the EEG.

3.3. *Gamma scalp topographies*

Decreases in gamma power were associated with counterfactual stories in the two loci after the counterfactual sentences themselves. An intriguing fact, however, was that these gamma effects were not a unitary phenomenon, because they had either a frontal or a parietal distribution, depending on several factors. Thus the gamma activity decreased *at frontal sites* for counterfactuals at the medial position of new-related sentences. By contrast, a decrease in gamma power was found *at parietal sites* for counterfactuals at the end of new-related sentences. The systematic nature of the scalp distributions suggests that different neural networks could be involved in counterfactual meaning. Notice that neither the changes nor the distribution of the gamma power can be attributed to lexical factors, because in most of the statistical tests reported here, the same word, embedded in the same sentence, was contrasted under the two contextual conditions. Therefore, the frontal vs. parietal distributions necessarily provide an indication of high-order processes at the discourse level, rather than of different lexical networks. The frontal distribution of gamma power activity consistently associated with factuals in the first locus is analogous to the frontal gamma activity reported in other experiments and has been proposed as a marker of semantic unification processes at the sentence level (e.g. Bastiaansen and Hagoort, 2006; Varela et al., 2001). Since parietal gamma effects during language comprehension have hardly been reported in the literature, it is difficult to give a well-founded explanation of this effect in our data, although it might be related to differential wrap-up processes at the end of sentence.

A note of caution on the interpretation of gamma rhythms has been put forward recently. Specifically, gamma activity could be just an artifactual correlate of micro-saccadic eye-movements, rather than a brain signature of cognitive processes (e.g. Melloni et al., 2009; Yuval-Greenberg et al., 2008). However, this interpretation is unlikely here for two reasons. First, micro-saccadic gamma activity occurs in short-lived broadband bursts, whereas the gamma activity observed here is narrowband and extends to hundreds of ms after word onset, indicating true neuronal dynamics (Fries et al., 2008). Second, micro-saccadic gamma activity has a centro-parietal distribution, whereas the gamma activity we found has either a frontal or a parietal distribution, suggesting that different neuronal networks are involved in the two cases. In conclusion, it is reasonable to assume that the observed gamma effects directly reflect differential cognitive processes in the brain associated with factual and counterfactual contexts.

In conclusion, this paper offers neurocognitive data which are compatible with the dual meaning approach to counterfactuals, and provides a detailed view of how updating occurs when these structures are embedded in narratives. Notably, this paper offers an interpretable set of ERP effects and gamma power changes that are associated with counterfactual comprehension and integration at the discourse level. First, the updating or semantic unification processes are less efficient after listening to counterfactuals than after listening to factuals. Second, the dual meaning of counterfactuals is supported by the ERP data, especially in the more semantically constrained stories (instrumental). Third, the analysis of gamma oscillations was more sensitive than the standard ERP analysis to the dynamic properties of counterfactuals in narrative contexts. Finally, the modulation of ERPs by the specific content of the stories suggests that semantic and pragmatic factors also modulate updating processes under counterfactual contexts.

4. Experimental procedures

4.1. *Participants*

Thirty-five students of Psychology (mean age: 21 years; 23 women) from the University of La Laguna were recruited. Five were discarded from the analyses due to equipment malfunction or an excessive number of incorrect responses and motor artifacts (blinks). All were native speakers of Spanish, right-handed (mean score: 70 in the Edinburgh Handedness Questionnaire), with normal or corrected vision, and with no known neurological disorders. They received credits for their voluntary participation in the experiment.

4.2. *Materials and design*

We constructed 160 stories: 80 with instrumental and 80 with spatial content. Each story involved the following: a) an initial sentence, introducing the protagonist and a situation, b) a critical sentence describing a new situation in either a factual or a counterfactual version, and c) a target continuation sentence referring either to the initial situation (herein initial-related) or to the new situation (herein, new-related). Each story was written in four experimental versions resulting from manipulating the context and the continuation sentence, namely: factual/new-related, factual/initial-related, counterfactual/new-related, and counterfactual/initial-related. Lexical factors (length and frequency) were checked for the content words of the continuation sentences (see Table 2). Although words in the spatial stories are generally more frequent than in instrumental stories, no significant differences were found among conditions in any pairwise comparison. We also established the plausibility of the continuation sentences with respect to the preceding factual and counterfactual contexts. Thirty-one students of psychology of the University of La Laguna (none of them participated in the main experiment) were given one of four lists containing spatial and instrumental items in the four experimental conditions. They were asked to judge in a 5-points scale how plausible was the continuation sentence with respect to the previous factual or counterfactual context. The means and standard deviations for spatial stories were as follows: counterfactual initial-related: $M=4.40$, $SD=.60$; counterfactual new-related: $M=1.65$, $SD=.63$; factual initial-related: $M=1.91$, $SD=.81$; and factual new-related: $M=4.40$, $SD=.64$. Concerning instrumental stories the obtained scores were: counterfactual initial-related: $M=4.30$, $SD=.61$; counterfactual new-related: $M=1.82$, $SD=.86$; factual initial-related: $M=2.3$, $SD=.94$; and factual new-related: $M=4.50$, $SD=.59$. As expected, the statistic contrasts showed that initial-related continuations were judged more consistent in counterfactual than in factual contexts, both in spatial stories ($t(30)=15.76$, $p<.0001$), and in instrumental stories ($t(30)=9.32$, $p<.0001$), whereas the new-related continuations were judged more consistent in factual than in counterfactual contexts, in spatial stories ($t(30)=17.2$, $p<.0001$), as well as in instrumental stories ($t(30)=14.4$, $p<.0001$). The homologous spatial and instrumental conditions did not differ significantly in continuation plausibility, except in one case: factual instrumental initial-related continuations were judged more plausible than factual spatial initial-related continuations ($t(30)=2.7$, $p<.01$). This difference, however, is not very relevant here because, as we have seen, it conflicts with rather than explains the results obtained in this study.

Four counterbalanced sets of 160 stories each were created resulting from the different assignments of the story content to the experimental conditions. Participants were assigned to one of the counterbalanced sets, thus receiving a total of 160 stories, or 40 in each version (20 instrumental and 20 spatial). Table 2 and Appendix A show examples of stories. The experiment employed a factorial design with 2 Content (instrumental/spatial)×2 Context (factual/counterfactual)×2 Continuation (initial-related/new-related) as within-participant factors.

4.3. *Procedure*

The participants sat in a comfortable chair in a dimly lit room at an approximate distance of 70 cm from the screen. Following application of the electrodes, the experiment began with the instructions for the task being displayed on the computer screen, followed by eight training trials. The stories were given auditorily through loudspeakers, except for the first clause of the continuation sentence, which was presented visually, one word at a time. A previous pilot study had found that this cross-modal presentation reduced participants' fatigue, and it also allowed for the controlling of the onset and duration of each critical word presentation, which was required for the ERP and TF analyses. Participants were instructed to listen and read for comprehension and to answer questions when required. While listening to the auditory part of the stories, they had to keep their eyes fixed on a point on the screen. The experimental session was split into two blocks, although the participants could interrupt the session at any time to rest.

The structure of each trial was as follows: The prompt "LISTEN" appeared on the screen and remained there for 2 s, then followed by a fixation point that remained on the screen while the participant listened to the story context. The first five words of the continuation sentence were presented

visually and were time-locked to the EEG recording as the first (verbal phrase) and second (noun) ERP locus, respectively. Each word remained on the screen for either 400 ms (nouns and verbs) or 300 ms (function words), and each was followed by a blank of 200 ms, except for the last sentence word, which was followed by a blank of 600 ms. About 35% of the trials were followed by a sensibility judgment task. Half of the questions corresponded to correct sentences and participants were to respond "YES" by pressing the "Q" key on the keyboard. The remaining questions followed incorrect (incoherent) sentences and the participants were to respond "NO" by pressing the "P" key. The question remained on the screen until the participant's response was entered or for a maximum of 5 s. To ensure participants' attention, a feedback message was given after their responses: *bien* (right) or *mal* (wrong).

Each session lasted approximately 90 min. We tested *a posteriori* whether participants' attention decayed over the course of this lengthy session. The number of errors in the sensibility judgment task did not differ between the first and second block (16% and 14%, respectively; $F(1, 29) = 2.30$, $p = .14$) nor did response times (1142 ms and 1122 ms, respectively; $F(1, 29) < 1$), therefore we can assume that participants' performance was stable. Errors did not differ either between factual and counterfactual stories, or between initial-related and new-related continuations, although they were more frequent in spatial than instrumental stories ($F(29) = 5.86$; $p < .02$).

4.4. *EEG recording and analyses*

We used a high-density EEG montage, with 58 thin Ag/AgCl electrodes mounted on an elastic cap that fit over the head at locations Fp1, Fp2, Fpz, Af3, Af4, F1, F2, F3, F4, F5, F6, F7, F8, FZ, Fc1, Fc2, Fc3, Fc4, Fc5, Fc6, Fcz, C1, C2, C3, C4, C5, C6, Cz, Cp1, Cp2, Cp3, Cp4, Cp5, Cp6, Cpz, T7, T8, TP7, Tp8, P1, P2, P3, P4, P5, P6, P7, P8, Pz, PO3, PO4, PO5, PO6, PO7, PO8, POz, O1, O2, and Oz following the standard 10/20 system. We eliminated 7 electrodes (T7, T8, C1, C6, P7, PO7, and PO8), because they contained an excessive number of artifacts in several participants. Four Ag/AgCl electrodes (10 mm in diameter) were also connected to the amplifier; one was placed on the canthus of the right eye and another under the left eye to record ocular movements. The remaining two electrodes were placed on the mastoids (one behind the right ear and the other behind the left ear), with the two mastoid electrodes serving as references for the others. Inter-electrode impedance was kept below 5 KΩ. The biosignals were processed by a Neuronic amplifier in a 0.05–100 Hz band and digitized with a sampling rate of 200 Hz. Stimuli were presented with the target time-locked to the EEG recording system using the ERTS software (http://www.berisoft.com/).

The EEG signals at the selected loci were prepared for two different kinds of analyses: an Event-Related Potentials (ERP) analysis to reveal whether endogenous components such as N400 or P600 distinguish between factual and counterfactual meaning, and a TF analysis to explore the oscillatory dynamics of EEG in a wide range of frequencies. The choice of time windows for ERP/EEG analysis for each locus was based on both theoretical and statistical criteria. Specifically, the non-parametric statistical method of permutations (included in the Neuronic EP Workstation package) was applied to estimate pairwise *t*-test comparisons between levels of a variable at each raw data-point. Segments that involved significant point-to-point comparisons for at least 75 consecutive ms in the permutation analyses (see Lage-Castellanos et al., 2010), and corresponded to ERP components described in the literature were selected as time-windows for further analyses.

The first locus was a continuous recording of the verbal phrase in the continuation sentence. Each subject's data were averaged relative to the verb onset along a 1900 ms range (−200 to 1700 ms). In this long time window, we obtained significant results in two epochs: the 115–235 ms epoch (the verb P200), and the 1400–1650 ms epoch (the noun N400). Analyses of these epochs provide information on discourse-based integration processes (consistency effects) following factual or counterfactual contexts. Finally, in the second locus, corresponding to the final word of the continuation sentence (a noun), the subject's individual data were averaged from −200 to 1000 ms relative to word onset. The 350–600 ms epoch (in the range of the N400 component) was selected using the permutation criterion. This component may be sensitive to consistency and wrap-up processes at the end of the sentence.

In order to reveal event-related changes in power for the different frequency components of the EEG, TF representations of the single trial data were computed using the multitaper approach described by Mitra and Pesaran (1999). In a frequency range from 20 to 90 Hz, 7-Hz frequency-smoothing windows and 300 ms time-smoothing windows were used to compute power changes in frequency steps of 2.5 Hz and time steps of 2 ms. TF representations were averaged for each subject for each electrode channel, in a time window from 100 ms before onset of the critical word to 900 ms after onset, separately for each of the conditions. The resulting subject-averaged power changes were expressed as a relative change from the 100 ms reference interval before the critical word. This resulted in an ERD/ERS-like measure of relative power change (Pfurtscheller and Aranibar, 1979; Pfurtscheller and Lopes da Silva, 1999). The significance of the difference between conditions was evaluated by means of a cluster-based random permutation test (see the section on statistical analysis).

4.5. *Statistical analyses*

Analyses of variance (ANOVAs) were performed for each epoch with the ERP data, using the mean amplitude values of each subject in each experimental condition. To address the effect of the violation of sphericity, the Greenhouse–Geisser correction was used when necessary. Two sets of ANOVAS were performed for each locus with 2 Content (instrumental/spatial), 2 Context (factual/counterfactual), and 2 Continuation (new-related/initial-related) factors used as within-participant factors. The first set of ANOVAs included Region as an additional factor, consisting of a repeated measure factor with two 19-electrode regions of interest: the fronto-central (Fp1, Fp2, Fpz, AF3, AF4, F1, F2, Fz, F3, F4, F5, F6, F7, F8, Fc3, FC4, FCz, FC5, Fc6) and the centro-parietal (C3, C4, CP1, CP2, CPz, CP3, CP4, CP5, CP6, TP7, TP8, P1, P2, PZ, PO3, PO4, POZ, PO5, PO6). When a significant interaction between

Region and any other variable was obtained, new analyses were run for each region separately. The second set of ANOVAs included Hemisphere (left/right) as a repeated measure factor. Hemisphere was introduced by removing the midline electrodes and contrasting the homologous electrodes on either side of the scalp. However, the analyses with Hemisphere will be not reported on here, because no significant effects were found.

The statistical significance of the differences between conditions for the TF representations of power change was evaluated by a cluster-based random permutation approach for the full set of 51 electrodes. We used this statistical approach mainly because of its elegant handling of the multiple-comparisons problem. The approach naturally takes care of interactions between channels, time points and frequency bins by identifying clusters of significant differences between conditions in the time, space and frequency dimensions, and effectively controls the Type-1 error rate in a situation involving multiple comparisons. The procedure is briefly described here (for a more detailed description of the approach, see Maris and Oostenveld, 2007).

First, for every data point (sensor-TF point) a simple dependent-samples *t*-test is performed (giving uncorrected p-values). All data points that do not exceed a pre-set significance level (here 5%) are zeroed. Clusters of adjacent non-zero data points are computed, and a cluster-level test statistic is calculated for each cluster by taking the sum of all the individual t-statistics within that cluster. Next, a null distribution is created as follows: subject averages are randomly assigned to one of the two conditions 500 times, and for each of these randomizations, cluster-level statistics are computed. For each randomization, the largest cluster-level statistic is entered into the null distribution. Finally, the actually observed cluster-level test statistics are compared against the null distribution, and clusters falling into the highest or lowest 2.5th percentile are considered significant. This procedure only allows for pairwise comparisons. Therefore, the statistical analysis of the TF data was based on pairwise comparisons between relevant conditions, instead of specifying a full-factorial 2×2×2 model.

The TF significant results reported here correspond to the gamma-band effects (30–90 Hz). We originally also analyzed separately the power changes in a low frequency window (2–20 Hz), although we did not obtain any significant effects related to the experimental manipulations. Consequently, we decided not to report them in the article. Crucially, however, the absence of effects in the lower frequency ranges excludes the possibility that the reported gamma-effects are the results of harmonics of effects in the lower frequency range.

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Appendix A. Spatial story

Initial situation:

Rene had been shipwrecked and he had spent 3 days navigating in a life raft. Suddenly he saw a helicopter flying towards the shore.

Critical sentence (new situation):

- Factual: Because the pilot located him in the ocean, he rescued him to take him to land.
- Counterfactual: If the pilot had located him in the ocean, he would have rescued him to take him to land.

Continuation sentence

- Related to initial situation: Rene *shouted to the pilot / in desperation* and saw him pass him by.
- Related to new situation: Rene *thanked the pilot / for his action* and asked for some cold water.

[Rene había naufragado y llevaba 3 días navegando en una balsa. De pronto vio a lo lejos un helicóptero volando hacia la costa.

Factual: Como el piloto lo localizó en el océano lo rescató para llevarlo a tierra.

Counterfactual: Si el piloto lo hubiera localizado en el océano lo habría rescatado para llevarlo a tierra.

Related to initial situation: Rene *gritó al piloto / con rabia* y comprobó que pasaban de largo.

Related to new situation: Rene *agradeció al piloto / su acción* y pidió agua fresca.]

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