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Automaticity of higher cognitive functions: Neurophysiological evidence for unconscious syntactic processing of masked words

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ABSTRACT

Models of language comprehension assume that syntactic processing is automatic, at least at early stages. However, the degree of automaticity of syntactic processing is still controversial. Evidence of automaticity is either indirect or has been observed for pairs of words, which might provide a poor syntactic context in comparison to sentences. The present study investigates the automaticity of syntactic processing using event-related brain potentials (ERPs) during sentence processing. To this end, masked adjectives that could either be syntactically correct or incorrect relative to a sentence being processed appeared just prior to the presentation of supraliminal adjectives. The latter could also be correct or incorrect. According to our data, subliminal gender agreement violations embedded in a sentence trigger an early anterior negativity-like modulation, whereas supraliminal gender agreement violations elicited a later anterior negativity. First-pass syntactic parsing thus appears to be unconsciously and automatically elicited. Interestingly, a P600-like modulation of short duration and early latency could also be observed for masked violations. In addition, masked violations also modulated the P600 component elicited by unmasked targets, probably reflecting that the mechanisms of revising a structural mismatch appear affected by subliminal information. According to our findings, both conscious and unconscious processes apparently contribute to syntactic processing. These results are discussed in line with most recent theories of automaticity and syntactic processing.

1. Introduction

Brain processes are traditionally divided into those that are automatic and those that are controlled (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1984). Automatic processes require little attentional control, are faster, do not use limited capacity recourses and therefore they do not engage the executive control systems. In contrast, controlled processes involve conscious attention, are slower, and engage limited capacity and executive control resources. Most recent theories of automatic processing propose more flexibility and context-adaptability of unconscious automatic processing than the classical theories do, by considering a bidirectional interaction between unconscious and executive control processes that might facilitate this adaptability (for a review see: Kiefer, 2002).

An open question in neurolinguistics is to determine the degree of automaticity of the syntactic processing. At first glance, syntax analyses seem to be very fast and not requiring conscious control or attention (e.g., Hasting & Kotz, 2008). In this regard, most widely accepted models propose that syntactic processing is automatic at least at early stages (Fodor & Frazier, 1980; Friederici, 1995; Friederici & Kotz, 2003; Gorrell, 1995; Inoue & Matsuzawa, 2007). However, according to recent evidence it remains unclear to what extent syntactic parsing might be performed automatically even in a first-pass and whether it needs the continuous contribution of conscious perception (Batterink, Karns, Yamada, & Neville, 2010; Hasting & Kotz, 2008).

Research on syntactic processing has led to two types of models: serial and interactive. Serial approaches propose that initial parsing processes are automatic, restricted to syntactic knowledge and phrase structure rules, and are independent of semantic and pragmatic information (e.g., Frazier & Fodor, 1978; Hahne & Friederici, 1999). Interactive models, in turn, propose that different

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aspects of language interact continuously during sentence comprehension (e.g., MacDonald, 1993; McClelland and Rumelhart, 1981; Boutonnet, Athanasopoulos, & Thierry, 2012). The main aim of this article is to investigate the automaticity of syntactic processing by presenting subliminal adjectives either syntactically correct or incorrect embedded in consciously perceived sentences that could also be syntactically correct or incorrect. As discussed below, unconscious stimulation ensures automatic processing, although both conscious and unconscious stimulation may contribute to automatic processing.

The automaticity of syntax can be approached by means of event related potentials (ERP) due to their high temporal resolution. To date, two functionally distinct ERP components related to syntax have been analyzed; anterior negativities and P600.

According to some authors, two types of anterior negativities with different onsets appear depending on the type of syntactic violation. A left anterior negativity (LAN) is typically seen to morphosyntactic errors, such as gender, number, or subject–verbs agreement violations (e.g. "The athletes is running"), typically appearing between 300 and 500 ms in left frontal electrodes. However, the laterality and anterior location of the component are not consistent across studies (e.g., Guajardo and Wicha, 2014; Hagoort, 2003a; Kutas Van Petten, & Kluender, 2006), so that more anterior and central distributions are also commonly reported (e.g., Barber & Carreiras, 2003, 2005; Molinaro, Vespignani, & Job, 2008). On the other hand, an ELAN (for early LAN), appearing between approximately 100 and 300 ms, is usually observed in response to word category violations, with phrase structure violations such as "the pizza was in-the eaten" (Hahne & Friederici, 1999, 2002). Whether LAN and ELAN conform two functionally different modulations remains unclear, however. For example, the LAN has also been found for word-category violations (Friederici & Meyer, 2004; Hagoort, 2003a; Hinojosa, Martin-Loeches, Casado, Muñoz, & Rubia, 2003). In addition, early anterior negativities are also observed for morphosyntactic violations (Hagoort, 2003b; Münte & Heinze, 1994) and specifically for gender agreement violations (Deutsch, Bentin, & Katz, 1999). Accordingly, the functional dissociation between LAN and ELAN might not apply (e.g., Hagoort, 2003a; Kaan, 2007; Steinhauer & Drury, 2012).

Anterior negativities seem to reflect first parsing processes, the detection of a morphosyntactic mismatch, difficult or rare processing of correct grammatical structure, the inability to assign the incoming word into the current phrase structure (Friederici, 1995; Hagoort, 2003a; Hahne & Friederici, 1999; Rösler, Pechmann, Streb, Rder, & Henninghausen, 1998), or some aspects of working memory operation (King & Kutas, 1995; Makuuchi et al., 2009; Martin-Loeches, Munoz, Casado, Melcon, & Fernandez-Frias, 2005; Weckerly & Kutas, 1999). The P600, a late component traditionally observed to syntactic anomalies but also reported to semantic anomalies (van Herten, Kolk, & Chwilla, 2005), appears between 600 and 900 ms after the onset of the anomaly in centro-parietal electrodes. This component is supposed to reflect costs of repair and revision of structural mismatches and/or integration processes between semantic and syntactic information (Friederici, 2002; Kuperberg, 2007; Martin-Loeches, Nigbur, Casado, Hohlfeld, & Sommer, 2006).

Most probably, anterior negativities reflect the most automatic and unaware part of the syntactic processing, as this component, in contrast to the P600, seems neither affected by the probability of encountering a violation (Hahne & Friederici, 1999) nor by task demands (Hahne & Friederici, 2002). The P600 may index therefore the more controlled mechanisms associated with syntactic processing (Münte, Heinze, & Mangun, 1993). Friederici (1995, 2002) has suggested a neurocognitive model of language comprehension mainly based on ERP findings. According to this model, syntax processing takes place in three consecutive phases: structure building based on word category information (reflected on ELAN component), syntactic-relational processing (LAN), and revision and repair processes (P600). However, this model would not hold if, as mentioned, the functional dissociation between ELAN and LAN were not applicable, and indeed Hasting and Kotz (2008) have reported highly automatic early ERP effects for morphosyntactic anomalies. They presented two types of violations local subject–verb agreement and word category violations implemented in two-word utterances with strictly controlled acoustic properties and identical violation points. In two experiments with varying task demands, anterior negativities with an onset at 100 ms were elicited in response to both violation types and independently of the allocation of attentional resources. As also mentioned, recent evidence also suggests that even first-pass syntactic parsing might not be performed automatically (Hasting & Kotz, 2008), while it has been questioned whether the continuous contribution of conscious perception is necessary for syntactic processing (Batterink et al., 2010). Consequently, the necessity of further research into the automaticity of syntactic processes seems warranted.

A suitable way of inquiring into the automaticity of syntactic processes can be approached by means of the dissociation between conscious and unconscious perception. Indeed, whereas automatic processes can be triggered by both conscious and unconscious stimuli, it can be ensured that processing occurs automatically for unconscious perception (Kiefer, Schuch, Schenck, & Fiedler, 2007). In this regard, several authors have successfully investigated the automaticity of brain processes by presenting masked visual stimuli. Interestingly, moreover, it is well demonstrated that masked unconscious stimuli trigger cognitive processes that can influence decision and action (Kiefer, 2007; Kiefer, Adams, & Zovko, 2012). The main goal of the current study is to investigate the automaticity of the syntactic processing of sentences using a masked priming paradigm, where syntactic violations were presented under subliminal viewing conditions to ensure that processing occurs automatically, with no contribution of intended, controlled processes.

To this aim, subliminal adjectives, which could be either correct or incorrect relative to the sentence being processed supraliminally (gender agreement violations between the supraliminal noun and the subliminal adjective) were shortly presented prior to the presentation of supraliminal adjectives that could in turn also be correct or incorrect relative to the sentence in progress. Accordingly, the sentences structure was: [determiner] – [noun] – [subliminal adjective] – [mask (#####)] – [supraliminal adjective] – [verb]. To minimize physical mismatch the same adjective was subliminally and supraliminally presented, though it could vary in a 2×2 factorial design as a function of the morphosyntactic correctness value relative to sentential structure. Thus, a supraliminal correctness × subliminal correctness factor design was used, where each sentence could be presented in 4 different conditions: (1) subliminal correct – supraliminal correct (C–C), (2) subliminal correct – supraliminal incorrect (C–I), (3) subliminal incorrect – supraliminal correct (I–C), and (4) subliminal incorrect – supraliminal incorrect (I–I) (Table 1). Gender agreement violations were specifically used to minimize physical mismatch between conditions, as in Spanish the final letter of the word usually marks the gender ("o" for masculine and "a" for feminine in most cases).

According to theories of automaticity of syntactic processing, particularly at its earlier stage, anterior negativities should be expected not only for conscious violations but also for unconscious violations. Accordingly, subliminal agreement violations should exhibit anterior negativities despite the supraliminal correctness of the sentences. Recent theories (for a review see: Kiefer, 2002) that propose a bidirectional interaction between the automatic processing and the executive control settings that modulate later

Table 1
Stimuli samples resulting from combining subliminal and supraliminal factors.

Supraliminal	Subliminal	
	Correct	Incorrect
Correct	(1) *Cor-Cor* e.g.: (a) El detective privado ####### privado investiga. (b) La sopa cocida ##### cocida bulle. {{The detective $_{[mas.]}$ private $_{[mas.]}$ ####### private $_{[mas.]}$ investigates.} {The soup $_{[fem.]}$ cooked $_{[fem.]}$ #### cooked $_{[fem.]}$ boils.}	(3) *Incor-Cor* e.g.: (a) El detective privada ####### privado investiga. (b) La sopa cocido ##### cocida bulle. {The detective $_{[mas.]}$ private $_{[fem.]}$ ####### private $_{[mas.]}$ investigates.} {The soup $_{[fem.]}$ cooked $_{[mas.]}$ #### cooked $_{[fem.]}$ boils.}
Incorrect	(2) *Cor-Incor* e.g.: (a) El detective privado ####### privada investiga. (b) La sopa cocida ##### cocido bulle. {The detective $_{[mas.]}$ private $_{[mas.]}$ ####### private $_{[fem.]}$ investigates.} {The soup $_{[fem.]}$ cooked $_{[fem.]}$ #### cooked $_{[mas.]}$ boils.}	(4) *Incor-Incor* e.g.: (a) El detective privada ####### privada investiga. (b) La sopa cocida ##### cocido bulle. {The detective $_{[mas.]}$ private $_{[fem.]}$ ####### private $_{[fem.]}$ investigates.} {The soup $_{[fem.]}$ cooked $_{[mas.]}$ #### cooked $_{[mas.]}$ boils.}

Non-literal translations (noun-adjective order inverted) into English.
Where mas. = masculine and fem. = feminine.

controlled processes justify possible subliminal effects on the controlled P600 component.

2. Methods

2.1. Participants

Twenty-four native Spanish speakers (17 females, 7 males) ranging from ages 18 to 40 (average 22.5) participated in this experiment. They all had normal or corrected-to-normal vision and had no documented history of reading difficulties or neural or psychiatric disorders. All were right-handed, with mean handedness percentage scores of 82.2%, ranging from 40 to 100%, according to the Edinburgh Handedness Inventory (Oldfield, 1971). The study was carried out according to the Declaration of Helsinki and approved by the ethics committee of the Centre for Human Evolution and Behaviour, UCM-ISCIII, Madrid, Spain. Prior to the experiment, subjects gave their informed consent and were remunerated at the end.

2.2. Materials

Experimental material consisted of 180 Spanish sentences that proved to be able to elicit both anterior negativity and P600 components in previous experiments, where sentence structure was [determiner] – [noun] – [adjective] – [verb] (Jimenez-Ortega et al., 2012; Martin-Loeches et al., 2012; Martin-Loeches, Sel, Casado, Jimenez, & Castellanos, 2009). However, in the present experiment we inserted a subliminal presentation of the same adjective followed by a mask, between the noun and the adjective in its standard (supraliminal) presentation. Resulting in the following structure: [determiner] – [noun] – [subliminal adjective] – [mask] – [supraliminal adjective] – [verb]. Following the methodology successfully used in previous masked priming linguistic experiments, subliminal adjective and mask were presented during around 17 ms each on a computer monitor, synchronously with the screen refresh (refresh rate = 16.67 ms ≈ 17 ms) (e.g., Kiefer & Martens, 2010; Van den Bussche, Van den Noortgate, & Reynvoet, 2009). The mask, ensuring unconscious perception of the subliminal word, consisted of repeated hash keys of previous adjective length (i.e., for a 4 letters adjective the mask was ####).

The supraliminally presented adjective could be either correct relative to the sentence, or present a gender agreement violation. In addition, the same adjective subliminally presented could also be syntactically correct or incorrect. Accordingly, we generated four versions of the same sentence varying on subliminal and supraliminal correctness: (1) subliminal correct – supraliminal correct (C–C), (2) subliminal correct – supraliminal incorrect (C–I), (3) subliminal incorrect – supraliminal correct (I–C), and (4) subliminal incorrect – supraliminal incorrect (I–I) (Table 1). A total amount of 720 sentences resulted from the combination of these factors in the original 180 sentences. These combinations ensure that all the 180 sentences were presented in different conditions, thus balancing the masculine and the feminine form presentation of both subliminal and supraliminal adjectives. Furthermore, regular Spanish adjectives were used to minimize physical mismatch, thus the masculine form ended in vowel – o (e.g. *privado*) and the feminine form ended in vowel – a (e.g. *privada*) (see Table 1).

The 720 combinations were distributed in 4 stimulation sets to avoid sentence repetition, hence controlling undesirable variables such as word frequency or word length effects, among others. Each stimulation set was therefore composed of the initial 180 sentences, but divided into 4 subsets of 45 trials each, one for each type of combination ((1) C–C, (2) C–I, (3) I–C, and (4) I–I). This way, no sentence was repeated across subsets, and no type of combination for a given sentence was repeated across sets. Subjects were randomly assigned to one of the sets (6 subjects per set), so that a given subject viewed each of the 180 sentences just once and in one type of combination. Within each set, the sentences appeared randomly.

We also included 120 fillers within each set. Fillers also incorporated an embedded subliminal presentation of a word. There were 60 short fillers with this structure: [determiner] – [subliminal noun] – [mask] – [supraliminal noun] – [verb]. The other 60 were long fillers with this structure: [determiner] – [noun] – [adjective] – [verb] – [subliminal complement] – [mask] – [supraliminal complement]. As in target sentences, the mask consisted of repeated hash keys of the previous subliminal complement length (i.e., for a 5-letter complement the mask was #####). Half of the fillers were syntactically correct and the remaining ones were incorrect. All the same fillers were included within each presentation set.

2.3. Procedure

Stimuli were presented white-on-black on a LCD screen, controlled by Presentation® Software. Subject's eyes were located 65 cm from the screen. Sentences, either in the experiment or in the post-test (see below), were presented word-by-word in the center of the screen, with visual angles around 0.8°–4° in width.

Subjects performed a syntactic correctness decision task based on the supraliminal adjective for every sentence in the experiment, by pressing one of two keys. Responses were given with the index and the middle fingers of the left or right hands. Hand assignment to judgment was counterbalanced. Subjects were requested not to blink during the presentation of the sentences in order to reduce ocular artifacts.

The beginning of each trial was signaled by a fixation cross that appeared during 500 ms, followed by the sentence, presented word-by-word, with 300 ms inter-stimulus-interval (ISI) and 600 ms of stimulus onset asynchrony SOA, except for the subliminal adjective and the mask for which the exposition time was adjusted to a screen refresh (≈17 ms). Every sentence was presented in the same format: the first word began with a capital letter and the sentence was finished with a full stop. After a 1 s interval, a question mark appeared during 1.5 s for the subject to answer. Inter-trial interval was 1 s (Fig. 1).

The session started with a training period, where a sample of 16 representative sentences not included in the experiment was presented. There were breaks after every 60 trials.

After the experimental procedure and the EEG recording, subjects performed a post-test to assess the unconscious perception of the subliminal stimuli. The post-test consisted in the presentation of 40 of the 180 initial sentences randomly selected (10 of each condition). Responses were given by pressing one of two keys, with the index and the middle fingers of the same hand. After the presentation of each sentence, the following question was asked: "*Did you notice anything other than the sentence?*" The possible answers were: "Yes" or "No". If the answer was "No" then the next experimental sentence was presented. If the subjects answered, "Yes", the following question was shown: "What have you noticed?". Subjects could choose between two answers: "*#####*" *or* "*Other*". Subjects were instructed to chose "*Other*" if they noticed an additional stimulus apart from the hash keys and the supraliminal sentence. If they chose "*Other*", they were asked to inform verbally about it. The presentation settings for the sentences in the post-test were identical to those used during the experiment, but after the sentence presentation, with 1 s delay time the first question was presented for 1.5 s or until the subject answered; if the answer was yes, then the second question was also presented for 1.5 s or until a response was given. Inter-trial interval was also 1 s.

2.3.1. EEG recordings

The electroencephalogram (EEG) was recorded from 27 tin electrodes embedded in an electrode cap (ElectroCap International) with Brainamp amplifier. Electrodes locations were: Fp1, Fp2, F7, F3, Fz, F4, F8, FC3, FC4, FT7, FT8, T7, C3, Cz, C4, T8, TP7, CP3, CP4, TP8, P7, P3, Pz, P4, P8, O1 and O2, plus right mastoid (M2), according to the extended 10/20 International System (American Electroencephalographic Society, 1991). All electrodes were referenced to the left mastoid (M1). Bipolar horizontal and vertical electrooculograms (EOG) were recorded for artifact monitoring. Electrode impedances were kept below 3 kΩ. The signal was continuously recorded with a bandpass from 0.01 to 30 Hz at a sampling rate of 250 Hz.

2.3.2. Data analysis

The continuous EEG record was divided into 1100 ms epochs, beginning 200 ms before the onset of the subliminal adjective, i.e., the epochs were time locked to the onset of the subliminal adjective, establishing a baseline starting at − 200 ms. The method described by Gratton, Coles, and Donchin (1993) was used to correct vertical (blinks) and horizontal eye movements. The artifacts were semi-automatically

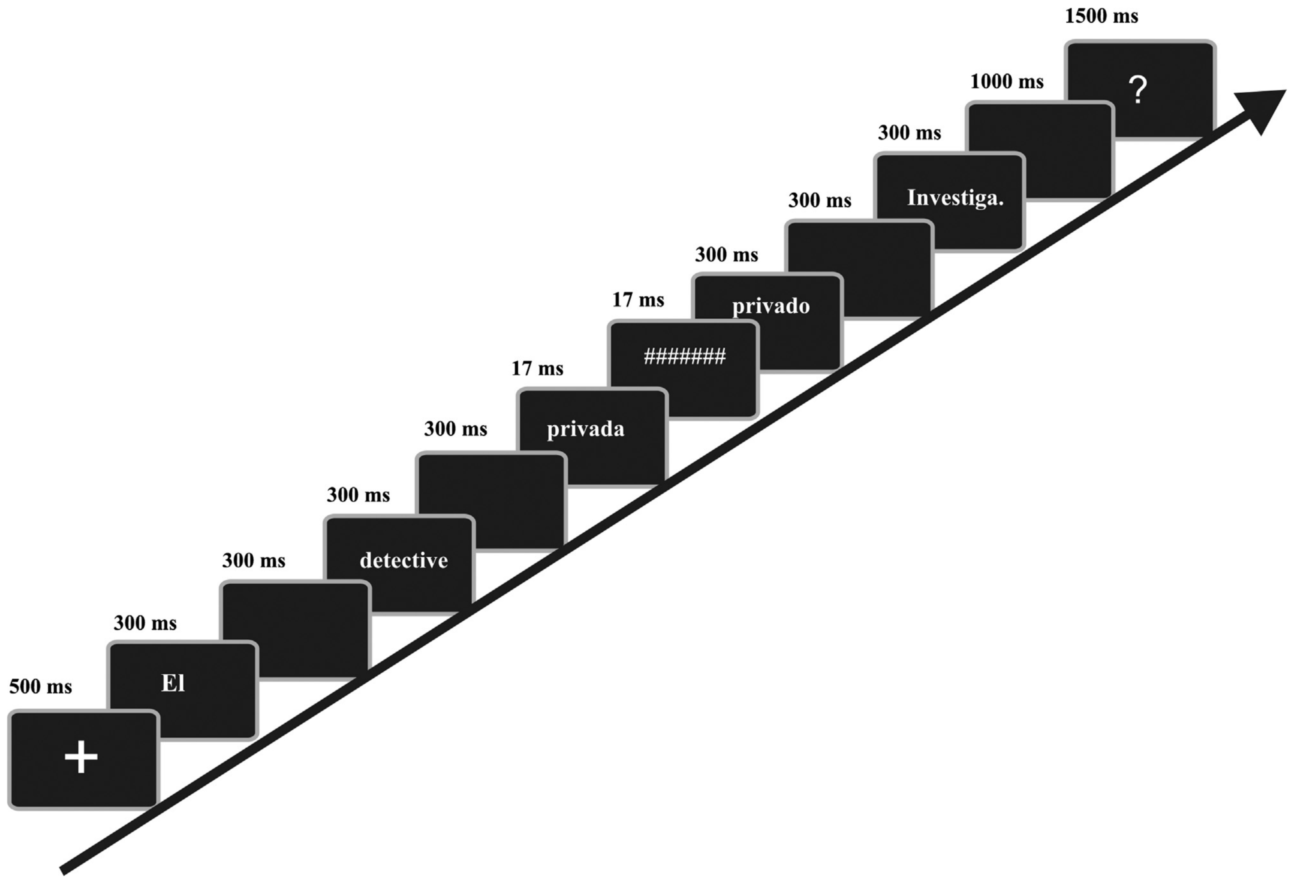

Fig. 1. Schematic representation of the stimulation procedures. The sentence judged for correctness was presented word-by-word and, included two presentations of the same adjective, subliminally and supraliminally. Both adjectives could be either syntactically correct or incorrect. Stimuli and black screen duration are indicated above and below the time axis, respectively.

rejected offline, by eliminating epochs exceeding ±100 μV in any of the channels. Remaining epochs that contained artifacts were eliminated throughout after a visual inspection. The data were re-referenced off-line to average mastoids. Those epochs that had incorrect responses in the syntactic correctness decision task were also eliminated from data analysis. Overall, the mean rejection rate was 25.76% of the epochs and at least 20 trials could be analyzed for every condition.

Statistical analyses were calculated by means of repeated-measures ANOVAs in which electrodes were grouped according to the following regions: left anterior (mean activity of Fp1, F7, F3, FT7), right anterior (Fp2, F8, F4, FT8), left central (T7, FC3, C3, CP3), right central (T8, FC4, C4, CP4), left posterior (TP7, P7, P3, O1), right posterior (TP8, P8, P4, O2). Thereafter, the ANOVAs included four factors: region (three levels: anterior, central, posterior), hemisphere (left, right), subliminal correctness (correct, incorrect) and supraliminal correctness (correct, incorrect). Where appropriate, the Greenhouse–Geiser correction for violations of the sphericity assumption was applied and post hoc tests were Bonferroni-corrected.

Time windows for measuring the syntactic ERP were selected on visual inspections of the waveforms. Mean amplitudes were measured in the following time windows: subliminal anterior negativity-like effects (100 to 300 ms), supraliminal anterior negativity and subliminal P600-like effects (450–550 ms), and finally supraliminal P600 (early effects: 600–700 ms and late effects: 700–800 ms).

3. Results

3.1. Behavioral data

In reference to the sentence correctness decision task, the total error rate was low (Ms = 8.47%). As in the ERP data, subjects' erroneous responses where excluded from the data analyses. Neither supraliminal correctness, subliminal correctness, nor interaction effects were found for error rates ($F(1,23) = .53$, $p > .1$; $F(1,23) = 2.8$, $p > .1$; $F(1,23) = .76$, $p > .1$, respectively).

A main effect of Supraliminal Correctness factor was observed for reaction times ($F(1,23) = 9.40$, $p < .01$), being longer for the supraliminal correct conditions than for the incorrect ones (Ms = 519.99 vs 484.84 ms).

The results in the post-test revealed that all the subjects detected the mask at some point along the session, but only five subjects (less than 10% of the cases) were aware of the subliminal word presentation previous to the mask. However, none of them could successfully identify it.

3.2. ERP data

Visual inspection of the ERPs revealed a long sustained anterior negativity (anterior negativity-like effects) between 100 and 300 ms for subliminal violations (Figs. 2 and 3). Furthermore, between 450 and 550 ms, a fronto-central anterior negativity appeared for supraliminal incorrectness. Interestingly, a positive posterior modulation (P600-like effects) for subliminal incorrectness seems to appear at this time window. Between 600 and 700 ms, supraliminal violations triggered a P600 component. Finally, at later stages – between 700 and 800 ms –, the P600 component to supraliminal violations was modulated by subliminal violations. Fig. 3 displays the main results as a function of the grammaticality of the subliminal and supraliminal adjectives.

3.2.1. Subliminal anterior negativity-like effects (100–300 ms)

ERP ANOVAs analyses revealed a significant interaction between subliminal correctness × region interaction ($F(2,46) = 3.92$, $p < .05$), whereas the subliminal and supraliminal correctness main factors were not significant ($F(1,23) = 2.75$, $p > .1$; $F(1,23) = .17$, $p > .1$, respectively), as was the case for the remaining interactions (*all Fs* < 2,3). To test Subliminal Correctness effects according to the

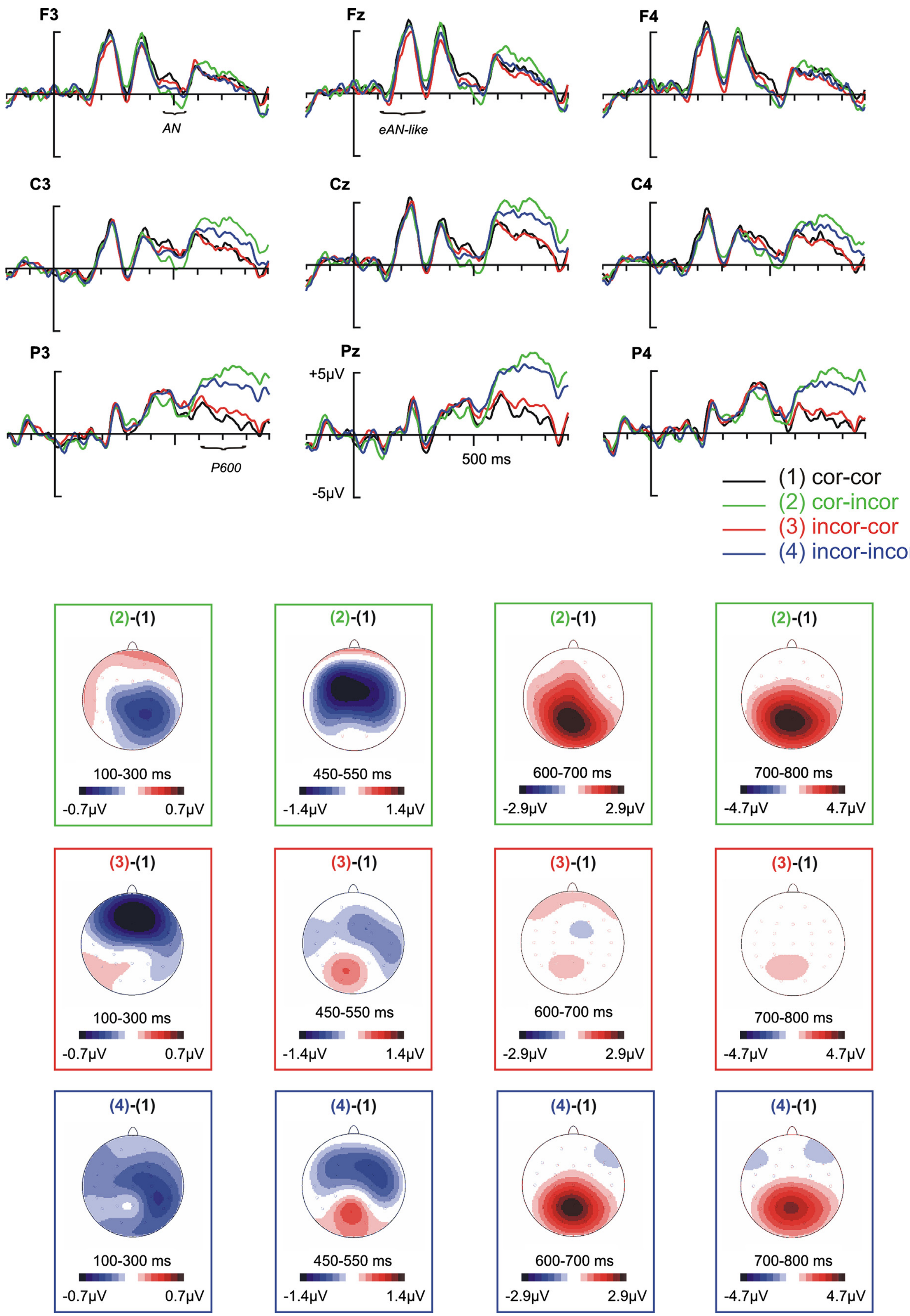

Fig. 2. ERPs to each condition resulting from combining subliminal and supraliminal factors. Top: ERP waveforms of all conditions at selected electrodes. Bottom: difference maps of the three conditions including any type of syntactic error minus the completely correct condition, in the analyzed time windows. Please note that color scales are adjusted to each time window individually.

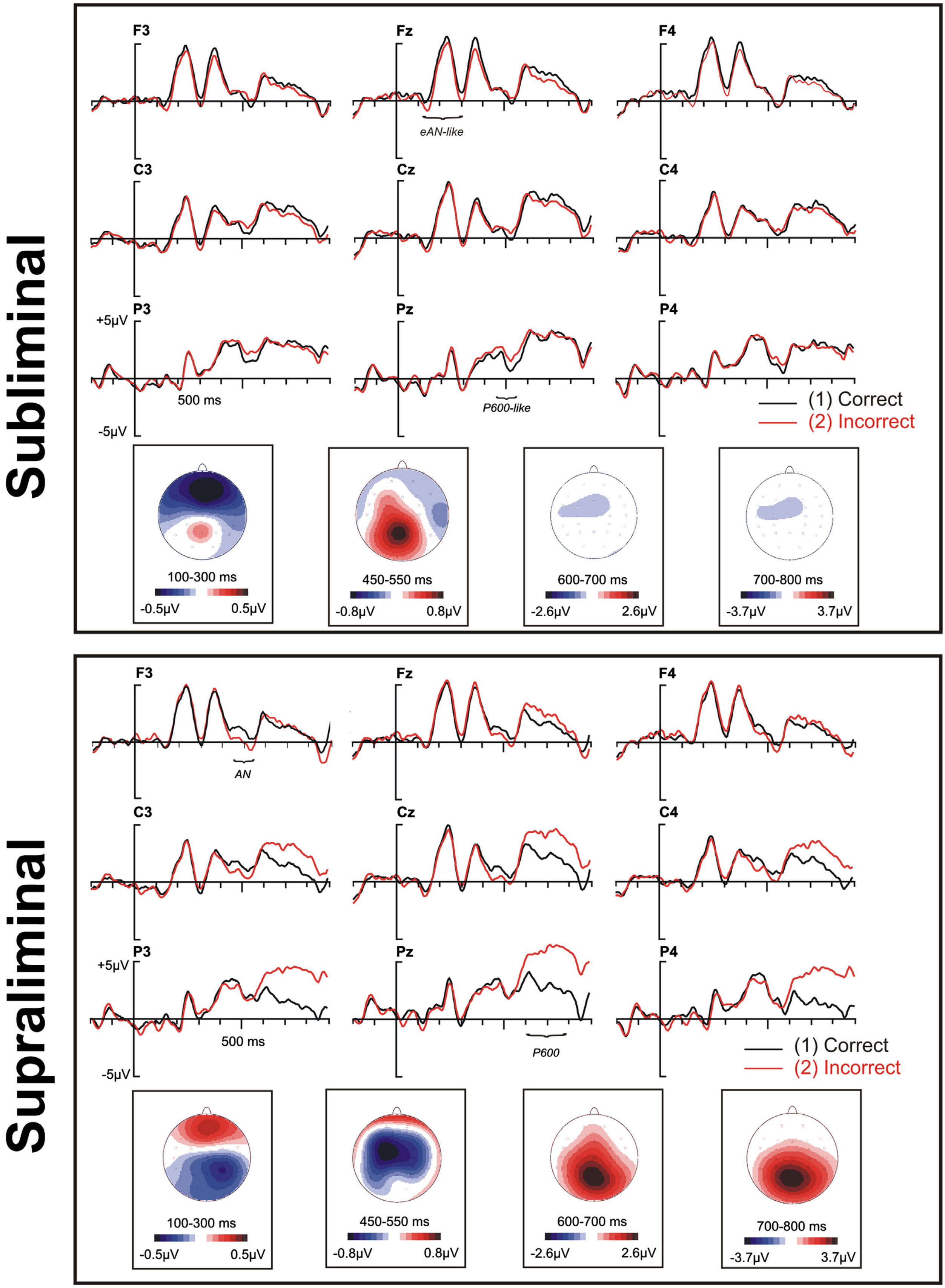

Fig. 3. ERPs as a function of grammaticality of the subliminal (top) and supraliminal (bottom) adjectives. ERP waveforms at selected electrodes and difference maps resulting from the incorrect vs. correct differences. Please note that color scales are adjusted to each time window individually.

region, we calculated t-tests between subliminal correct and subliminal incorrect conditions for each region. Significant effects were exclusively obtained for the anterior region ($t(23) = 2.42$, $p < .05$). For central and posterior regions significant effects were not obtained ($t(23) = 1{,}18$, $p > 0.5$ and $t(23) = .363$, $p > 0.5$, respectively). Therefore, subliminal correctness effects are located in the anterior region of the scalp.

3.2.2. Supraliminal anterior negativity and subliminal P600-like effects (450–550 ms)

We observed a significant main effects of supraliminal correctness factor ($F(1,23) = 4.51$, $p < .05$) in the 450–550 ms window. No significant effects were observed among all other factors or interactions (all $Fs < 2.4$), with the exception of a subliminal correctness × region × hemisphere significant effect ($F(1,23) = 4.73$, $p < .05$). To further test this significant interaction, we calculated six related t-tests comparing subliminally correct vs. subliminally incorrect for each region within each hemisphere. Effects appeared just for the left posterior region ($t(23) = -2.96$, $p < .01$), all other t-test comparisons did not reach significant effects (all $ts < 1{,}16$).

3.2.3. Early P600 (600–700 ms)

ANOVA analyses of the early P600 window revealed significant effects of supraliminal correctness main factor ($F(1,23) = 17.62$, $p < .001$) and in interaction with region ($F(2,41) = 11.4$, $p < .001$). Three related t-test (supraliminally correct vs. supraliminally incorrect) for each region revealed significant effects for central and posterior regions ($t(23) = -4.1$, $p < .001$; $t(23) = -5.07$, $p < .001$), while no effects were observed for the anterior region ($t(23) = -.16$, $p > .05$).

3.2.4. Late P600 (700–800 ms)

Between 700 and 800 ms, as in the former window, both supraliminal correctness factor and supraliminal correctness × region interaction were significant ($F(1,23) = 29.69$, $p < .001$; $F(26,598) = 25.89$, $p < .001$, respectively). Supraliminal correctness × subliminal correctness and supraliminal correctness × subliminal correctness × region interactions also yielded significant effects ($F(1,23) = 6.01$, $p < .05$; $F(2,46) = 3.13$, $p < .05$, respectively). Further ANOVA analyses (subliminal correctness × supraliminal correctness) within each region, revealed subliminal × supraliminal trend or significant effects for central and posterior regions ($F(1,23) = 4.02$, $p = .057$; $F(1,23) = 45{,}5.13$, $p < .01$, respectively), but not for the anterior one ($F(1,23) = .63$, $p > .05$). Subsequent t-test analyses for the posterior region revealed significant differences between all conditions ((1) vs. (2): $t(23) = -7{,}54$, $p < 0.001$); (1) vs. (4): $t(23) = -5.22$, $p < .001$); (2) vs. (3) $t(23) = -7{,}05$, $p < 0.001$, (2) vs. (4): $t(23) = 3{,}716$, $p < .01$ (3) vs. (4) $t(23) = -5.27$, $p < 0.001$) except for the comparison between conditions (1) C–C vs. (3) I–C ($t(23) = -1.52$, $p > .1$). Similarly, for the central region significant effects were observed between all conditions ((1) vs. (2): $t(23) = -4{,}93$, $p < 0.001$); (1) vs. (4): $t(23) = -2.81$, $p < .05$); (2) vs. (3) $t(23) = -4{,}72$, $p < 0.001$, (2) vs. (4): $t(23) = 2{,}81$, $p < .05$ (3) vs. (4) $t(23) = -2.79$, $p < 0.05$) except for (1) C–C vs. (3) I–C comparison ($t(23) = 0{,}91$, $p > .1$). Therefore, for posterior and central regions of the brain significant differences were observed between all conditions except for conditions (1) C–C and (3) I–C, where the supraliminal adjective was presented in the correct form.

4. Discussion

In the present study we investigated the automaticity of the syntactic processing by presenting subliminal adjectives that could be correct or incorrect (gender agreement violations) prior to supraliminally presenting adjectives that could as well be syntactically correct or incorrect relative to an on-going sentence.

The main ERP findings were a long-lasting early anterior component (AN-like effect) between 100 and 300 ms for unconscious masked violations followed by an anterior negativity component (spreading from frontal to central regions of the scalp) between 450 and 550 ms for conscious violations. Interestingly, in this latter time-window, a posterior positive effect (P600-like) was triggered by unconscious violations. This was followed by P600 effects between 600 and 700 ms for unmasked violations, and finally a modulation of this P600 component by unconscious masked violations from 700 to 800 ms.

The most striking result of this study is that masked gender violations were able to elicit an early anterior negativity between 100 and 300 ms followed by a posterior positivity. The distribution of the anterior negativity to subliminal violations appeared more anterior and central than the typical left anterior distribution though, as reviewed in the introduction, this is within the range of normal topographies reported for anterior negativities to grammatical violations, including gender violations (Molinaro et al., 2008). Hence, it might be considered as an anterior negativity-like (AN-like) effect. In parallel, the distribution of the posterior positivity to masked violations did not accurately exhibit the typical symmetrical distribution for the standard P600 effect. Despite this differences in distribution, we refer to this effect as P600-like effect for the following reasons: it appeared in response to (subliminal) morphosyntactic violations, the timing with respect to the subliminal AN-like effect approaches that of the standard P600 with respect to standard anterior negativities, and finally its distribution is maximal over posterior electrodes. Accordingly, it seems that subliminal morphosyntactic (gender) violations may elicit similar ERP pattern as supraliminal (conscious) violations, that is, a frontal negativity followed by a posterior positivity. The timing for either of these two modulations appeared earlier than the typical modulations for supraliminal stimuli. To the best of our knowledge, this is the first direct evidence of the automaticity of syntax-related ERP modulations using subliminal presentations. Post-tests (see results section) confirmed that subjects were unaware of the masked adjective presentation. Therefore, according to our data, the human brain is capable of processing automatically and unconsciously syntactic information, detecting morphosyntactic anomalies.

The automatic early processes reflected in the AN-like modulation to subliminal violations seems to be very fast, taking place between 100 and 300 ms. According to Friederici's model (2011), morphosyntactic violations generally do not trigger an early anterior negativity. However our results are in line with those by Hasting and Kotz (2008), challenging, at least, the temporal sequence of Friederici's (2011) model for syntactic processing, which proposed that exclusively word category information processing occurs at early stages. Nevertheless, our data supports the idea of automaticity of early parsing processes proposed by Friederici (2011). We observed either early anterior negativities or late anterior negativities to identical gender agreement violations depending only on awareness (subliminal vs. supraliminal presentation). Accordingly, the early anterior negativity might be an index of syntactic automaticity rather than an index of pure category information processing. The idea of early anterior negativities reflecting automatic processing has influenced many well-regarded neurocognitive models (e.g., Hagoort, 2003a; Ullman, 2001; Schlesewsky & Bornkessel-Schlesewsky, 2013; for a review see: Steinhauer & Drury, 2012). In addition, this idea is in line with previous studies reporting early anterior negativities for morphosyntactic violations (e.g., Hagoort, 2003b; Münte & Heinze, 1994), or later anterior negativities to word category violations (Friederici & Meyer, 2004; Hinojosa et al., 2003). As concluded in an extensive review by Steinhauer and Drury (2012), the functional dissociation between early and late anterior negativities remains largely uncertain.

Between 450 and 550 ms a later anterior negativity appeared for conscious gender violation distributed over anterior and central regions of the scalp. The distribution and the temporal dynamic of this supraliminal anterior negativity supports those observed in classic experiments investigating morphosyntactic violations (e.g., Gunter, Friederici, & Schriefers, 2000; Kutas & Hillyard, 1980; see also Guajardo & Wicha, 2014) and previous research carried out in our laboratory using similar sentences (Hinojosa et al., 2003; Jimenez-Ortega et al., 2012; Martin-Loeches et al., 2012). Furthermore, anterior and central distributions are also commonly reported to morphosyntactic violations and specifically to gender violations (e.g., Barber & Carreiras, 2003, 2005; Molinaro et al., 2008). The topography of this anterior negativity and that obtained to subliminal violations do not seem to be identical, however, the latter appearing somewhat more anterior than the former. Nevertheless, both modulations displayed topographies resembling those reported in previous literature for anterior negativities to grammatical violations. As mentioned in the introduction, the topography of these modulations does not seem consistent across studies, or even within studies (e.g., Martin-Loeches et al., 2005). It remains unclear, however, if our subliminal and supraliminal negativities to grammatical violations can be considered as functionally equivalent. Further research is needed to clarify this point.

The anterior negativity to supraliminal violations was followed by a P600 exhibiting normal timing, amplitude, and topography (e.g., Martin-Loeches et al., 2006). The P600 component is believed to be an index of controlled mechanisms associated with syntactic processing (Münte et al., 1993), costs of repair and revision of structural mismatches and/or integration processes between semantic and syntactic information (Friederici, 2002; Kuperberg, 2007; Martin-Loeches et al., 2006). We have found, however, a P600-like modulation to masked violations, as well as an effect of these masked violations on the P600 to conscious violations. Our findings might indicate, on one hand, that not all the processes reflected by the P600 would be controlled and, on the other hand, that unconscious grammar processing elicited by gender-masked errors seems also to affect late controlled syntactic processes. Accordingly, the P600 component might be a general index of linguistic information integration, where not only semantics and syntax are combined but also conscious and unconscious data. Moreover, other types of information, such as emotional information, have also been reported to modulate P600 components (Vissers et al., 2010). The local and unconscious effects over sentential conscious processes indicate a flexibility of the syntactic processes as well as relevance of unconscious operations for this task. Indeed, the automatic nature of the syntactic processing does not imply blindness to context and other cognitive operations, as proposed by some syntactic models (Fodor, 1983; Fodor & Inoue, 1994; Friederici, 2002; Hagoort, 2003a; Hauser, Chomsky, & Fitch, 2002; Ullman, 2001, 2004). Nowadays, most recent theories of automaticity suggest that even unconscious processing is flexible and context dependent as a function of high level executive control settings (for a recent review: see Kiefer, 2002). This flexible concept of automaticity is a better model to explain recent evidence. Despite automaticity, syntactic processing can be modulated by other processes such as semantic, emotional information or even by a high working memory load (Jimenez-Ortega et al., 2012; Martin-Loeches et al., 2006; Vissers et al., 2010; Vos, Gunter, Kolk, & Mulder, 2001).

Why masked violations were able to trigger early anterior negativities and P600-like modulations preceding those elicited by supraliminal violations remains unexplained. It is also an open question whether this early timing is specific for gender violations or a common feature of all possible types of masked syntactic violations (e.g. number or word-category violation). With a SOA of 34 ms (between the onsets of the subliminal and the supraliminal adjectives) both types of information might actually be considered almost simultaneously, but this appears not to be exactly the case. It seems instead that the processes linked to subliminal information are rapidly prompted and/or that the processing of supraliminal information is delayed, by virtue of presumably automatic mechanisms that cannot be elucidated here.

In conclusion, subliminal gender agreement violations triggered an early anterior negativity between 100 and 300 ms, suggesting that syntactic processing might occur at early stages even under unconscious conditions. This would reinforce the arguments for the automaticity of early anterior negativities. An anterior negativity between 450 and 550 ms was also triggered by conscious syntactic errors, in line with most of the literature. In addition, along the later temporal segment unconscious syntactic errors also triggered a P600-like modulation. Further, unconscious syntactic processes also seemed to influence the later portions of the conscious P600 component. Accordingly, it seems that the more controlled mechanisms usually associated with the structural sentence processing presumably reflected by P600 modulations can also be affected by unconscious information.

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