Processing linguistic negation with and without truth-value evaluation: Evidence from N400 and theta oscillations

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Abstract

How linguistic negation is processed online has been a long-standing issue in psycho- and neurolinguistics. In this study, we investigated negation processing in two distinct types of sentences with truth-value evaluation (e.g., ‘A robin is a/not a bird’), and without (e.g., ‘The woman reads a/no book’), focusing on electroencephalogram (EEG) indices in terms of the N400 component, oscillatory power and inter-trial phase coherence (ITPC). Across both sentence constructions, we observed enhanced N400 and increased ITPC in the theta band for semantically unrelated target words, irrespective of negation. However, for the theta power, we observed distinct modulation effects of negation on semantic-relatedness for two types of sentence constructions. In addition, we showed that direct comparison between affirmative and negative target words led to effects in the N400 and theta power in a nuanced manner. Our findings provide novel evidence on a more interactive role of negation during online sentence processing.

Key words

N400; negation; truth-value; semantic congruency; theta power; theta ITPC

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Introduction

How the human brain processes linguistic negation is an ongoing issue in the psycho- and neurolinguistic literature, which has been examined under various perspectives, e.g., the mental representation of a negated concept (e.g., MacDonald & Just, 1989; Kaup, 2001), the temporal processing of sentence negation (e.g., Lüdtke et al., 2008; Haase et al., 2019; Spychalska et al., 2019; Wiswede et al., 2013), or the relevance of varying context conditions (Dudschig et al., 2019; García-Marco et al., 2019; Liu et al., 2019; Nieuwland, 2016; Tian & Breheny, 2016; Tian et al., 2016; Nieuwland & Martin, 2012; Bahlmann et al., 2011; Deutsch et al., 2009; Giora et al., 2009; Nieuwland & Kuperberg, 2008; Hasson & Glucksberg, 2006). In daily communication, linguistic negation is introduced under several circumstances. On the one hand, the negation operator potentially changes the truth-value of a statement, as in categorical relations based on world knowledge (*A trout is (not) a fish*, c.f., Fischler et al., 1983: 402) or semantic congruency (*Thoughts are (not) stripy,* c.f., Dudschig et al., 2019: 311). On the other hand, negation attenuates the activation of a concept within a proposition (*Elizabeth baked some bread but no cookies*, c.f., MacDonald & Just, 1989: 635), without necessarily falsifying a formerly true statement. However, it remains unclear if the two types of negation are processed similarly by the human brain.

The first type of negation has been classically investigated via the N400 component (Kutas & Federmeier, 2011; Lüdtke et al., 2008; Lau et al., 2008). A seminal study from Fischler et al. (1983) found that false affirmative and true negative conditions result in enlarged N400 amplitudes: Contrary to the expectation that the truth value of target words is fully reflected in the N400 time window, for the negative condition, the opposite result was found. Thus, the N400 component is explained as deriving primarily from the semantic relatedness between subjects and objects, regardless of the truth-value of a sentence. When the truth-value is rendered by means of the negation operator, it is not directly incorporated within the N400 time window. These findings from Fischler and colleagues have been replicated by a number of more recent studies (Dudschig et al., 2019; Haase et al., 2019; Wiswede et al., 2013), even when the categorical relations are presented in a pragmatically licensing context (Palaz et al., 2020). Together with the findings by Fischler et al. (1983), they are in line with the Two-Step-Simulation-Hypothesis proposed by Kaup et al. (2006). Accordingly, whereas the semantic relationship between target words and their sentences is reflected in the N400 time window, the negated truth of the target is incorporated at a later stage of sentence processing. Nevertheless, it remains open whether this hypothesis is applicable for all negation contexts. With regard to different violation contexts, Dudschig et al. (2019) found that, similar to previous studies (Haase et al., 2019; Wiswede et al., 2013), the N400 was not affected by negation in both contexts of semantic and world-knowledge violations. The effects in both violation types confirmed the predictive nature of the N400 in terms of semantic relatedness between critical words (Bornkessel-Schlesewsky & Schlesewsky, 2019; He et al., 2020; Lau et al., 2008), regardless of different violation types. Notably, in Dudschig et al. (2019) and in previous studies (Fischler et al., 1983; Haase et al., 2019; Wiswede et al., 2013), the target stimuli were either fully incongruent regardless of negation (e.g., *Thoughts are (not) stripy,* c.f., Dudschig et al., 2019 (semantic violation), or the negation word rendered the truth-value of a sentence (e.g., *Zebras are (not) stripy*, c.f., Dudschig et al., 2019 (world knowledge violation)). Furthermore, in both cases mentioned above, sentence structures imply that truth-value, i.e., whether the sentence is true or false, will need to be evaluated by the comprehender. However, negation is not always used in daily communications affecting truth-values (Autry & Levine, 2012; MacDonald & Just, 1989; Nieuwland, 2016; Nieuwland & Kuperberg, 2008). Rather, it is more commonly used to attenuate an established proposition (c.f., Kaup, 2001). For example, for breakfast, one may eat an egg, or may not eat an egg. Whether and how negation modifies the semantic processing on *eat–egg* (e.g., the N400) has not been thoroughly investigated. Therefore, while the majority of psycho- and neurolinguistic research has focused on negation in a context of truth value reversal (Kaup et al., 2006; Lüdtke et al., 2008; Dale & Duran, 2011) or violated conditions affecting the N400 component (Dudschig et al., 2019), how linguistic negation is processed with an attenuating function (MacDonald & Just, 1989; Kaup, 2001) remains an open question. To this end, here we investigate how the N400, as derived from the semantic relationship between words, is affected by negation in both of these two contexts, which we refer here as categorical relations (truth value function) and congruency relations (verb-object relatedness, attenuating function).

Besides the N400, remarkably, recent years have witnessed an emergence of literature focusing on the oscillatory aspects of the EEG on language processing (Bastiaansen & Hagoort, 2003; 2015; Wang et al., 2012; Lewis et al., 2015). Recent advances in this line of literature suggest the putative role of theta (3-7 Hz), beta (14-30 Hz) and gamma band oscillation (>30 Hz) with regard to semantic integration of congruency, behavioral task results and semantic retrieval processes (c.f. Prystauka & Lewis, 2019 for a review). Importantly, Hagoort and colleagues (2004) found dissociable time-frequency patterns for semantic versus world knowledge violations resulting in increase of theta power in semantic violations and gamma power increase world knowledge violations, while the N400 amplitudes were comparable. Therefore, it is worthwhile to investigate how theta and gamma oscillations are modulated by negation, to understand how negation affects the processing of categorical and congruency relations. Moreover, oscillatory effects in narrow-band power may be independent from phase modulations (as reflected in the inter-trial phase coherence, ITPC), which is another candidate neural index of semantic processing. Increased theta ITPC has been related to the processing of target words in low constraint sentences, connected to increased N400 amplitudes (Strauß, 2015), as well as of unpredictable target words (Rommers & Federmeier, 2018; Pu et al., 2020). Therefore, the analysis of ITPC may contribute to the understanding of the nature of ERP and theta band effects during sentence processing at semantic level. Thus, both theta power and ITPC may reveal in what way negation affects the lexico-semantic retrieval processes of target words. To our knowledge, no prior research has directly investigated whether negation affects oscillatory power and ITPC.

Next to the aim of disentangling the processing of categorical and congruency relations, our second research aim was to detect the direct inhibiting nature of negation, which might be reflected in both ERPs and oscillatory power. Beltrán et al. (2018) found a main effect of negation connected to negated sentence processing with a following Stop-Signal task. Negation processing interacted with inhibiting response behavior, as was reflected in inhibition-related N1 and P3 effects. The inhibiting nature of negation had also been found in de Vega et al. (2016), who found motor inhibition effects in delta- and theta power caused by negation of action verbs with increased frontocentral theta power in affirmative compared to negative conditions. However, it is noteworthy that the effects were interpreted as resulting from decreased action conflict management necessary after linguistic negation in order to solve NoGo trials, compared to Go trials, instead of the purely linguistic processing of negation (c.f., also Dudschig & Kaup, 2020). Nevertheless, Beltrán et al. (2019) replicated these findings and proved that the effects occurred regardless of the verb content. These effects indicate that inhibitory control mechanisms related to linguistic negation (also found e.g., in Mandarin, as in Liu et al., 2019) possibly influence sentence processing. Therefore, it remains open whether this inhibiting effect occurs similarly in different sentence contexts. That is why we directly compare effects between target words that directly follow affirmative vs. negative articles (i.e. *kein* / *ein* in German), since the potential inhibiting effect of negation would affect the semantic integration of negated concepts.

To address these outstanding issues, we conducted the current study, investigating both the ERP and oscillatory effects when processing sentence negation in German. Importantly, besides the classic design from Fischler et al. (1983) using sentences such as ‘A trout is a / no fish’ to describe categorical relations, we employ an additional stimulus set including verb-object relations such as ‘The woman reads a / no book‘. We hypothesize that, following prior research (Fischler et al., 1983; Spychalska et al., n.d.; Dudschig et al., 2019; Palaz et al., 2020), the N400 is mainly affected by the predictability of a sentence's target/ or critical word following negation. As reported in prior literature, in categorical relations we expect a clear interaction of negation and truth-value, based on the semantic relatedness of the content words. In congruency relations, despite expecting an N400 effect for semantic congruency violation, we refrain from making clear-cut predictions on how this N400 is affected by negation. Secondly, we expect dissociable effects in theta or gamma power with regard to the two stimulus types. Whereas in categorical relations (world knowledge violation), gamma oscillations possibly increase, an increase in theta power for semantically incongruent target words in congruency relations (semantic violation) is expected, reflecting increased lexical-semantic retrieval processes (Hagoort, 2004). In addition, an increase in ITPC might be found for more unpredictable, semantically incongruent sentence endings (Rommers & Federmeier, 2018). However, in what way negation affects theta power and phase coherence effects for the two contexts remains exploratory, since to our knowledge no studies have looked at negation on the semantic integration of target words *after* the negation operator. Inhibiting effects have been observed directly at the position of the negation word (de Vega et al., 2016, Beltrán et al., 2019), but not on affirmed or negated target words. Therefore, it is more or less speculative, whether the inhibiting power of negation reaches out until the processing of target words after negation processing. Time-frequency analysis and ITPC results might give insights on semantic retrieval demands (Pu et al., 2020), and possible inhibiting (de Vega et al., 2016) or even constraining effects, which negation might impose on during online sentence processing.

Methods

Participants

The study was obtained at the Neurolinguistic Lab of Johannes Gutenberg University in Mainz. Twenty-one right-handed, native German were included in the study, corresponding to the inclusion criteria for EEG measurements. The participants (11 male, 10 female, mean age = 24 years (range = 20-37 years)) had no neurologic, speech and language processing related impairment, no psychiatric medication, which was determined by a questionnaire before the experiment. They were informed about the procedure and gave informed consent to use the data for research and dissemination/publication purposes. All participants were included into the analysis. Ethical approval for EEG experimentation was obtained at the Deutsche Gesellschaft für Sprachwissenschaft, according to custom guidelines of the ethics committee.

Materials

Two types of sentence stimuli were constructed to investigate the processing of negation with and without truth-value evaluation (see **Table 1**). The first type directly replicates categorical relations as employed in (Fischler et al., 1983) (e.g., *A trout is (not) a <u>fish / tool</u>* [Eine Forelle ist k/ein Fisch / Werkzeug]). Here, the negation operator is relevant for evaluating the truth-value of a sentence. The second type describes semantic relations of action verbs to their accusative objects (e.g., *The woman reads a/no <u>book / bicycle</u> [Die Frau liest k/ein <u>Buch / Fahrrad</u>])*. Crucially, in the second type, the presence of negation words do not result in a reversed evaluation of the truth-value of the sentence. Conclusively, for each of type of stimuli, we manipulated (1) truth value / congruency [true or false (T or F) / congruent or incongruent (C or I)], and (2) negation [affirmative or negative (A or N)], leading to a fully factorial two-by-two design for each type of stimuli. We additionally manipulated typography conditions [bold case, uppercase or normal case] for the articles and negation operators for research questions outside the scope of the current study. Here, we collapsed the typographic conditions for the present analysis. Altogether, we used 90 sentences per condition, thus leading to 720 sentences (90 x 2 relation types (true / congruent vs. false / incongruent) x 2 polarities (affirmative vs. negative) x 2 sentence types) for each participant.

Categorical items	**Congruency items**
A trout is a fish. (True Affirmative, TA) *Eine Forelle ist ein Fisch.*	The woman reads a book. (Congruent Affirmative, CA) *Die Frau liest ein Buch.*
A trout is no fish. (False Negative, FN) *Eine Forelle ist kein Fisch.*	The woman reads no book. (Congruent Negative, CN) *Die Frau liest kein Buch.*
A trout is a tool. (False Affirmative, FA) *Eine Forelle ist ein Werkzeug.*	The woman reads a bicycle. (Incongruent Affirmative, IA) *Die Frau liest ein Fahrrad.*
A trout is no tool. (True Negative, TN) *Eine Forelle ist kein Werkzeug.*	The woman reads no bicycle. (Incongruent Negative, IN) *Die Frau liest kein Fahrrad.*

Table I. Example for the truth-value and congruency German sentences and their English translations. The target words are underlined.

In both sentence types, the sentences were matched in terms of length and frequency (dlexdb.de). For the categorical set, mean length was eight syllables / five words per sentence in each condition. Mean frequency of subjects was *M*= 0.65 logLemma frequency (*SD*= 0.51) and of objects was *M*= 1.66 logLemma frequency (*SD*= 0.45) For the congruency type, mean length of the sentences was 7 syllables (5 words in each condition). Mean frequency of verbs (*M*= 0.65 logLemma frequency, *SD*= 0.1) and objects (*M*= 1.68 logLemma frequency, *SD*= 0.27) resulted in conditions not differing from each other. For both sets, we additionally carried out a rating study to ensure congruency/ incongruency: The subject-object pairs and verb-noun pairs were distributed on four lists. Native-German adults (*n*= 61, mean age= 27.90 , range= 18-46 years), who did not participate in the EEG study, rated one fourth off all subject-object pairs in the truth value sentences on a five-point Likert-Scale in terms of congruency and familiarity (1= not congruent, not familiar, 5= congruent, familiar). The semantically congruent conditions (TA, FN) were rated as more congruent (*Median*= 5, SD=0.83) than the incongruent items (*Median*= 1, SD= 1.12) (Z= -43.28, p<0.001); the familiarity was also rated as more familiar for the congruent pairs (*Median*= 5, SD= 0.98) compared to the incongruent pairs (*Median*= 1, SD= 0.71) (Z= 11.64, p<0.001). Also, native-German adults (*n*= 58, mean age= 27.36 , range= 19-46 years), who did not participate in the EEG study, rated one fourth off all verb-noun word pairs in the congruency sentences, on a five-point Likert-Scale in terms of congruency and familiarity (1= not congruent, not familiar, 5= congruent, familiar). The congruent items were rated as more congruent (*Median*= 5, SD= 0.81) than the incongruent items (*Median*= 1, SD= 0.68) (Z= 11.66, p<0.001); the familiarity was also rated as more familiar for the congruent pairs (*Median*= 5, SD= 1.09) compared to the incongruent pairs (*Median*= 1, SD= 1.04) (Z= -47.66, p<0.001).

Procedure

After signing written consent, all participants sat comfortably in a sound-attenuating booth. The experimental stimuli were presented visually in the center of a TFT monitor (19 zoll), in blue letters against a black background. After starting a trial with an asterisk in the middle of the screen (duration: 500 ms), the experimental sentences were presented word by word (duration: 300ms) with an ISI of 200ms. Three question marks were presented in the middle of the screen 500 ms after the presentation of the sentences in orange letters to prompt responses for the experimental task. Participants were asked to judge the plausibility of the sentences as fast as possible (“Does the sentences make sense?”), by pressing the left (“Yes”) or right (“No”) button on a joystick. Yes and No response buttons were counter-balanced. The inter-trial-interval was 1000 ms. Each participant started with one brief practice block of eight practice sentences before the experimental session. The entire experimental session consisted of 720 pseudo-randomized stimuli in six blocks with short breaks in between, with a total length of 1.25 hours. All stimuli were presented in 4 pseudo-randomized lists, equally distributed across the participants.

EEG recording

The EEG was recorded from 26 Ag/ AgCl scalp electrodes within an elastic cap Easy*Cap International, Herrsching, Germany*), which conformed to the standard 10–20 system for electrode positioning (Jasper, 1958). The electrode positions were F7; F3; Fz; F4; F8; FC5; FC1; Fcz; FC2; FC6; T7; C3; Cz; C4; T8; CP5; CP1; Cpz; CP2; CP6; P7; P3; Pz; P4; P8; POz. All scalp electrodes were referenced online to the left mastoid. The ground electrode was positioned at the AFz. Horizontal and vertical eye movements were monitored by four eye electrodes that were placed above and below the participant’s right eye and at the outer canthus of each eye. Electrode impedance was kept below 10 kΩ. Scalp EEG was amplified by a BrainAmp Standard DC amplifier (Brain Products GmbH, Gilching, Germany) with sampling rate of 250 Hz. TTL triggers from stimulus and participants responses were presented with Presentation Software

(Neurobehavioral Systems, Berkeley, CA, USA), and were acquired with the EEG using Brain Vision Recorder (Brain Products GmbH, Gilching, Germany).

Behavioral Analysis

Whereas the EEG analysis was obtained for both stimulus sets separately, the behavioral data were analyzed across the two item sets. For accuracy rates and reaction times, we conducted a repeated measurement ANOVA with the factors sentence type, truth/ congruency, and negation.

EEG preprocessing and analyses

All EEG preprocessing and analyses were carried out using the Brain Vision Analyzer 2.1 (Brain Products GmbH, Gilching, Germany) and the fieldtrip toolbox for EEG/MEG analysis (Oostenveld et al., 2011). We applied two preprocessing pipelines separately for ERP and for time-frequency (TF) analyses.

Preprocessing. For the ERP analyses, we firstly applied a band-pass filter between 0.1 and 40 Hz to the raw continuous EEG and then re-referenced the data to the average of the two mastoids. EOG artifacts were manually identified and rejected via an infomax independent component analysis. The raw EEG was then segmented from -200 ms to 1000 ms around the onset of the target word. Segmented data were subjected to automatic muscle artifact rejection (z = 9) based on the amplitude distribution across trials and channels, as implemented in the Fieldtrip toolbox. For the TF analyses, we applied a band-pass filter between 0.1 and 125 Hz to the raw EEG. The artifact rejection procedure for both continuous and segmented data was analogous to the ERP analyses, except for the fact that we segmented a longer time window between -2.5 and 3.5 seconds based on the onsets of the target words.

ERP analyses. For analyses of ERPs, for each segment resulted from preprocessing, we applied a baseline correction based on the -0.2 to 0 seconds time window. Segments within a condition were then averaged within each participant across trials in the first step. Secondly, grand averaged ERPs were averaged across all participants. For statistical comparison, we used cluster-based permutation test (10000 permutations) in the electrode space for amplitudes averaged within the N400 (300-500ms) time window. The test was then conducted in the electrode space, with each electrode having on average 4.7 neighboring electrodes according to a template layout. A cluster in the permutation test contained at least three neighboring electrodes. We conducted statistical comparisons within each type of stimuli. As we were interested in the interaction between truth-value / congruency and negation, we compared 1) the effect of truth-value / congruency within each negation conditions (e.g., FA>TA and FN>TN separately), and 2) the truth-value / congruency difference between affirmative and negative conditions (e.g., (FA>TA) > (FN>TN)) for testing statistical significance of interaction effects. We did not directly compare the conditions of the two item sets, since the structure of the two sentences potentially confounded the effects of semantic relatedness. Therefore, all analyses were obtained for both item sets separately. We additionally report negation effects for semantically related and unrelated conditions in the supplement, comparing 1) the effect of negation within related conditions (e.g., TA>FN/ CA>CN and FA>TN/ IA>IN separately), and 2) the negation difference between related and unrelated conditions (e.g., (FN - TA) > (FA - TN)).

Time-frequency analyses. As we were interested in the theta and gamma frequency bands, for TF decomposition, we computed TF representations in two different frequency ranges to optimize the trade-off between time and frequency resolution. In the low frequency range (1-30 Hz), we applied a sliding window Hanning taper approach (3 cycles per window), in frequency steps of 0.25 Hz and time steps of 0.05 seconds. In the high frequency range (25-80 Hz), TF decomposition was carried out using a multi-taper approach (Mitra & Pesaran, 1999), with frequency smoothing factor of 0.2 in frequency steps of 2 Hz and time steps of 0.1 seconds. We focused our analyses therefore on oscillatory power and ITPC. Oscillatory power was interpreted based on baseline-corrected (-0.5 to -0.25 seconds) decibel change (dB). For statistical comparison of dB power and ITPC, we applied cluster-based permutation tests to test for statistical differences in the frequency bands of interest (theta, beta, and gamma bands). The tests were conducted in the time-electrode space, with neighborhood parameters comparable to the ERP analysis. Pairwise comparisons and interaction analyses were carried out analogous to the ERP analysis, with additional comparisons in the supplement.

Results

Behavioral results

The behavioral data was obtained from 21 participants. One participant was not included into the analysis. Mean values and standard deviations for accuracy rates and reaction times in each condition are shown in Figure 1. For both accuracy rates and reaction times, we conducted repeated measurement ANOVA with the factors sentence type, truth/congruency and negation. For the accuracy rates, there was a main effect of negation ($F(1,19) = 21.663$, $p<0.001$) with higher accuracy rates for affirmative conditions. A significant sentence type x negation interaction ($F(1,19) = 4.406$, $p=0.049$) showed larger negation effects in the categorical sentences ($p<0.001$) compared to the congruency sentences ($p=0.002$). A significant sentence type x truth/congruency x negation interaction revealed a significant truth-value x negation interaction only for the categorical sentences ($p=0.008$), but not the congruency sentences ($p=0.126$).

For the reaction times, across both item sets, a main effect of negation was found ($F(1,19) = 86.050$, $p<0.001$) with affirmative sentences responded to significantly faster than negative sentences, regardless of the truth value of the sentences. In the categorical sentences, true sentences revealed slightly larger negation effects than false but the interaction was not significant (p=0.281). Interestingly, FA was responded to faster than TN, and TA was responded to faster than FN. Thus, negation was reflected in the reaction times more prominently than the truth-value of the sentences, whereas the semantic relationship between subject and object was not consistently reflected in the reaction times: FN was not detected significantly faster than TN (p=0.794). For the congruency item set, negation revealed a main effect (p<0.001), whereas neither congruency resulted in a main effect (p=0.153), nor was an interaction found (p=0.596). Thus, sentence negation was a larger influence factor to reaction times than semantic congruency between verbs and objects.

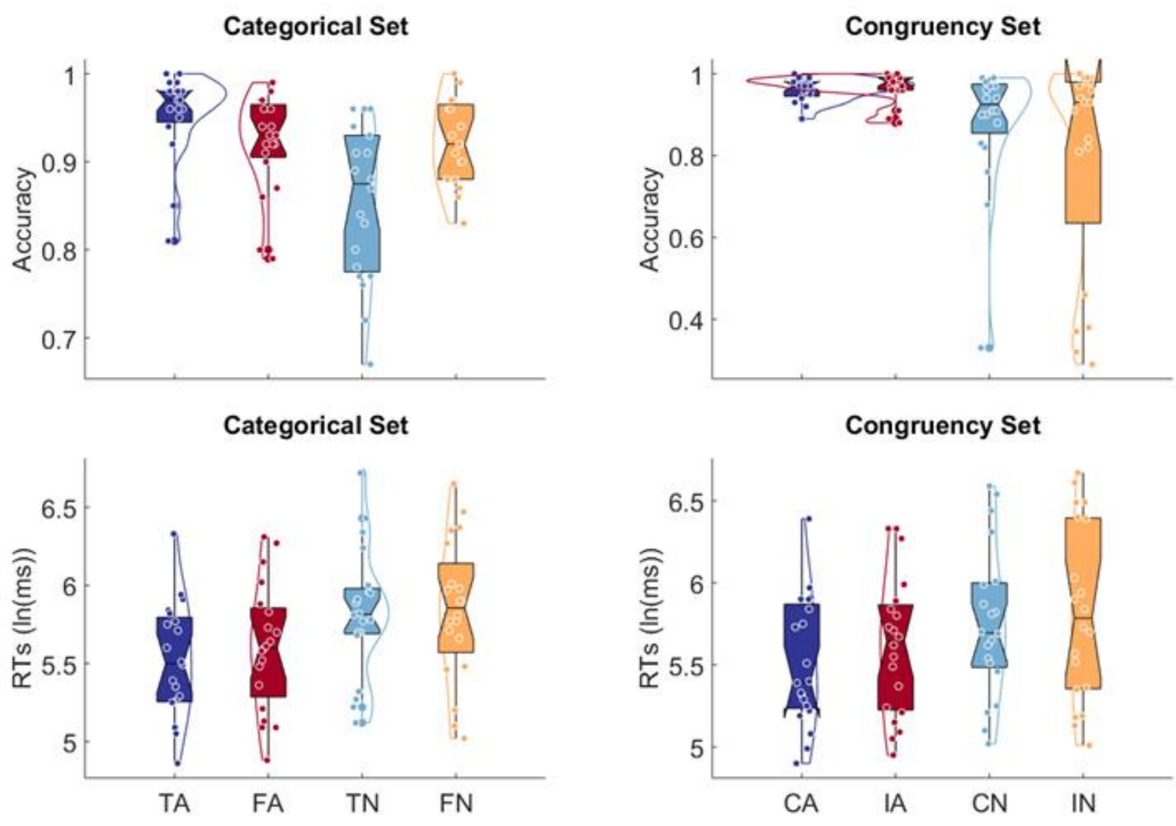

Figure 1. Boxplots for mean accuracy rates (upper plots) and reaction times (bottom plots) for each condition in *categorical sentences* (left) and *congruency sentences* (right).

N400

<u>Truth-value sentences.</u> We directly compared the N400 component within each type of sentences to reveal the role of semantic relatedness and negation on processing of truth-value and verb-object congruency (**Figure 2**). For the truth-value sentences, in the affirmative condition, false sentences, when compared with true sentences (FA>TA) elicited a widespread N400 effect ($p_{cluster}$<0.001, **Figure 2A, D**); in the negative condition, however, FN>TN elicited a widespread positivity in the same time window ($p_{cluster\text{-}min}$<0.001, **Figure 2C, D**). The interaction between truth-value and negation was significant ($p_{cluster}$<0.001, **Figure 2D**).

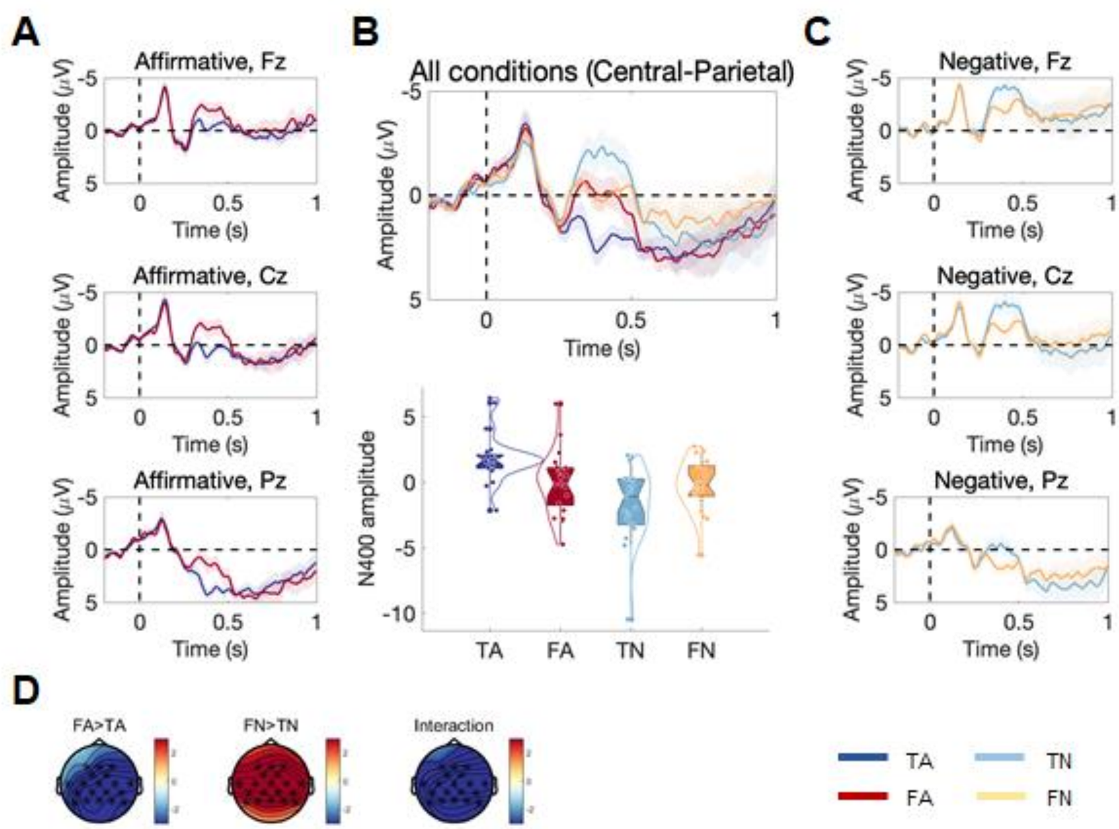

Figure 2. ERPs at the onset of the critical word for the *truth value sentences*. **Panel A**: ERPs for false vs. true affirmative sentences (FA>TA) at three midline electrodes FZ, Cz, and Pz. **Panel B**: ERPs averaged from nine central-

parietal electrodes (C3, Cz, C4, CP1, CPz, CP2, P3, Pz, P4), and box- and swarm-plots for individual subjects' N400 (300-500ms) amplitudes from these electrodes. **Panel C**: ERPs for false vs. true negative sentences (FN>TN) at three midline electrodes FZ, Cz, and Pz. **Panel D:** Scalp maps show t-values for statistical comparisons between FA>TA, FN<TN and their interaction ((FA>TA) < (FN<TN) analyses between 300-500ms, significant electrodes ($p<0.025$, FWE-corrected with cluster-based permutation test) are marked with asterisks.

<u>Congruency sentences.</u> For the congruency sentences (**Figure 3**), in the affirmative condition, when comparing incongruent and congruent sentences (IA>CA), we observed a central-parietal N400 effect ($p_{cluster}<0.001$, Figure 3D); in the negative condition, similarly, incongruent sentences showed an N400 in the same time window with similar scalp-distribution ($p_{cluster}<0.001$, **Figure 3D**). In addition, we observed no interaction between congruency and negation.

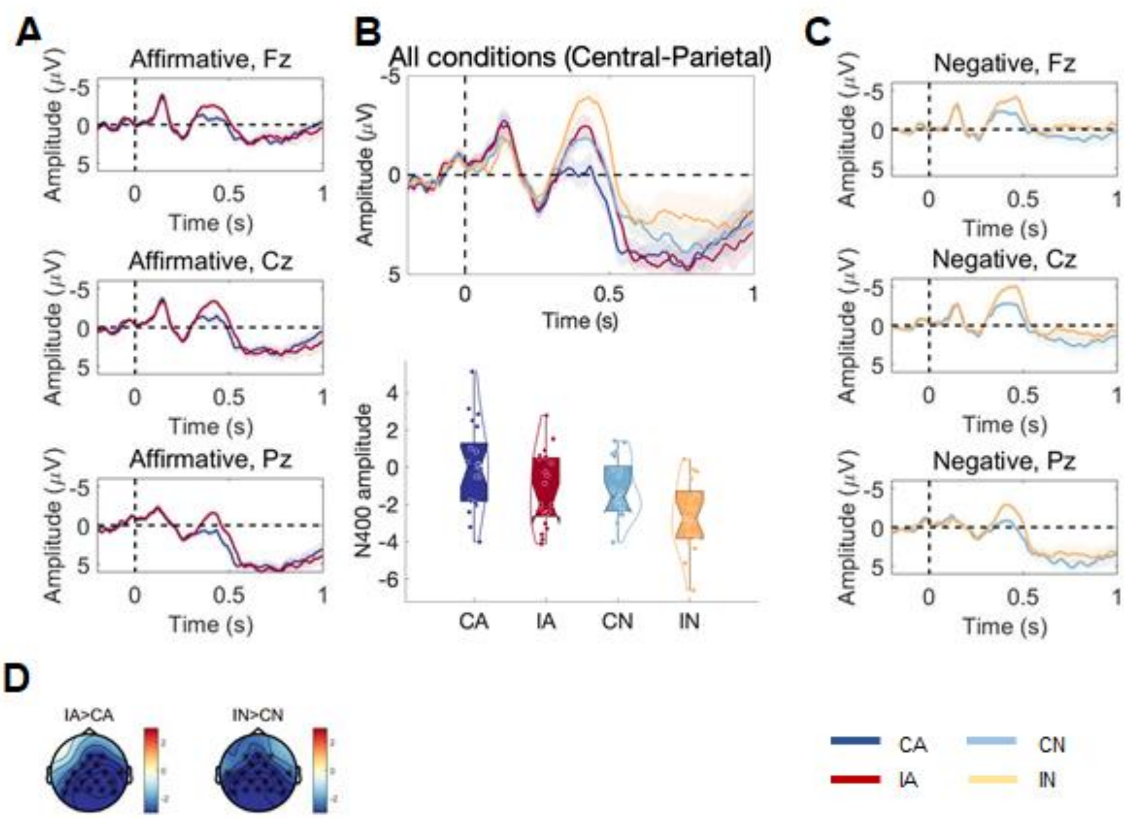

Figure 3. ERPs at the onset of the critical word for the *congruency sentences*. **Panel A**: ERPs for incongruent vs. congruent affirmative sentences (IA>CA) at three midline electrodes FZ, Cz, and Pz. **Panel B**: ERPs averaged from

nine central-parietal electrodes (C3, Cz, C4, CP1, CPz, CP2, P3, Pz, P4), and box- and swarm-plots for individual subjects' N400 (300-500ms) amplitudes from these electrodes. No significant interaction between congruency and negation was observed. **Panel C**: ERPs for incongruent vs. congruent negative sentences (IN>CN) at three midline electrodes FZ, Cz, and Pz. For all ERP waveforms, shaded areas indicate by-subject standard errors for respective conditions. **Panel D**: Scalp maps show t-values for statistical comparisons between congruent and incongruent conditions between 300-500ms, and significant electrodes (p<0.025, FWE-corrected with cluster-based permutation test) are marked with asterisks.

Theta power

<u>Truth-value sentences.</u> In the time-frequency analysis, we observed no effects in the beta and gamma band power for all experimental conditions. For the theta power (**Figure 4**), we found a significant power increase for the FA>TA comparison ($p_{cluster\text{-}min}$<0.001, **Figure 4D**) beginning at 450ms. Additionally, a negation x truth-value interaction was observed ($p_{cluster\text{-}min}$<0.001, **Figure 4B**).

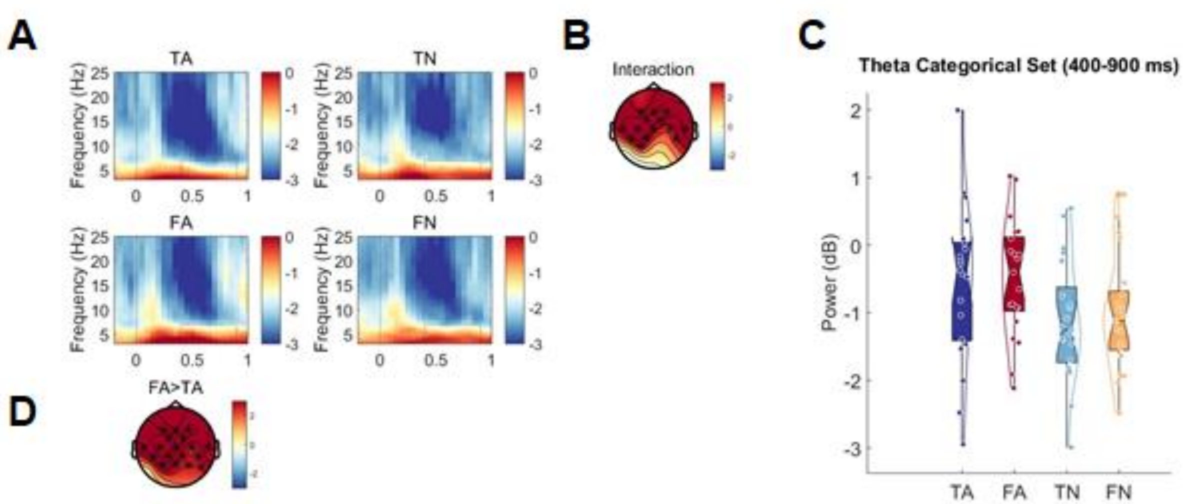

Figure 4. Theta power effects at the onset of the critical word for the *truth value sentences*. **Panel A**: averaged time-frequency power scalograms across Cz and Pz electrodes. **Panel B**: Scalp t-maps show interaction ((FA>TA) > (FN>TN)) analyses. Significant electrodes (p<0.025, FWE-corrected with cluster-based permutation test) are marked with asterisks, weak significances (two-tailed p<0.05, FWE-corrected) are marked with crosses. **Panel C**:

Box- and swarm-plots for individual subjects' theta power (400-900ms) amplitudes from Cz and Pz electrodes (as in Panel A). **Panel D:** Scalp t-maps show TA>FA analyses in the theta band (3-7Hz) between 400 and 900 ms (as outlined in Panel A).

<u>Congruency sentences.</u> For the congruency sentences, no effects in the beta and gamma band power were observed. For the theta power (**Figure 5**), we observed a significant power increase for the IA>CA comparison ($p_{cluster\text{-}min}$=0.0119, **Figure 5B**) beginning at 400 ms after onset target word. For the CN>CA comparison this effect was visible between 750 and 1000 ms ($p_{cluster\text{-}min}$=0.035, **Figure 5C**), and for the CN>IN comparison between 900 and 1000 ms ($p_{cluster\text{-}min}$=0.0246), but no significant difference between IA>IN ($p_{cluster\text{-}min}$=0.2289) conditions. In addition, no interaction was observed.

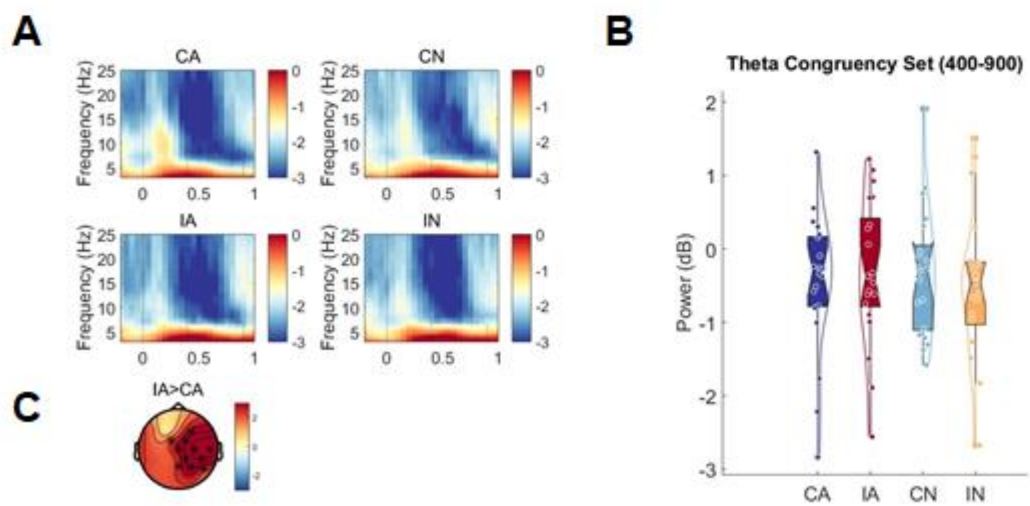

Figure 5. Theta power effects at the onset of the critical word for the *congruency sentences*. **Panel A**: Averaged time-frequency power scalograms across C4 and P4 electrodes. **Panel B**: Box- and swarm-plots for individual subjects' theta power (400-900ms) amplitudes from C4 and P4 electrodes (as in Panel A). **Panel C**: Scalp t-maps show IA>CA analyses in the theta band (3-7Hz) between 400 and 900 ms (as outlined in Panel A). Significant electrodes (p<0.025, FWE-corrected with cluster-based permutation test) are marked with asterisks, marginal significance (two-tailed p<0.05, FWE-corrected) is marked with crosses.

Theta ITPC

<u>Truth-value sentences.</u> For analyses of ITPC, we again observed no effects in the beta and gamma bands. In the theta band (**Figure 6**), we observed a significant ITPC increase for the FA>TA comparison ($p_{cluster}$=0.0056, **Figure 6D**), with a right frontal scalp distribution. We also observed a significant ITPC decrease for the TN>FN comparison ($p_{cluster}$=0.0072, **Figure 6D**), as well as a significant truth value x negation interaction ($p_{cluster-min}$=0.0014, **Figure 6B**).

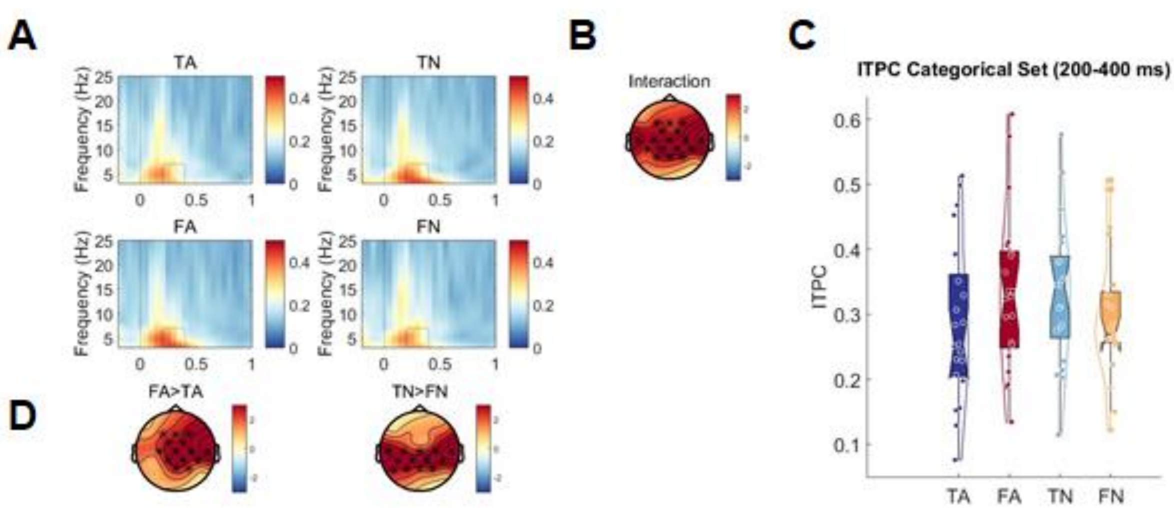

Figure 6. Theta ITPC effects at the onset of the critical word for the *truth value sentences*. **Panel A**: Averaged ITPC scalograms across Cz and Pz electrodes. **Panel B:** Scalp t-maps show the interaction ((FA>TA)>(FN<TN) analyses. Significant electrodes (p<0.025, FWE-corrected with cluster-based permutation test) are marked with asterisks. **Panel C:** Box- and swarm-plots for individual subjects' theta ITPC (200-400ms) amplitudes from Cz and Pz electrodes (as in Panel A). **Panel D**: Scalp t-maps show FA>TA (left) and TN>FN (right) analyses in the theta band (3-7Hz) between 200-400ms ms (as outlined in Panel A).

<u>Congruency sentences.</u> No ITPC effects in the beta and gamma bands were observed. In the theta band (**Figure 7**), we observed a significant ITPC increase for the IA>CA comparison ($p_{cluster}$=0.0099, **Figure 7C**), with a central-parietal distribution. We also observed a marginally significant ITPC decrease for the

IN>CN comparison ($p_{cluster-min}$=0.0431, **Figure 7C**). No interaction was observed for congruency x negation.

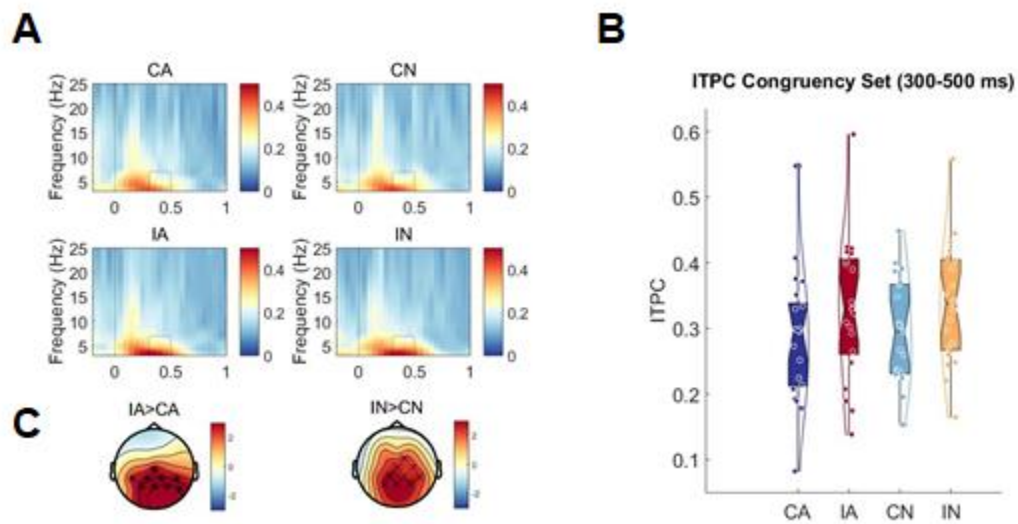

Figure 7. Theta ITPC effects at the onset of the critical word for the *congruency sentences*. **Panel A**: Averaged ITPC scalograms across Cz and Pz electrodes. **Panel B**: Box- and swarm-plots for individual subjects' theta ITPC (300-500 ms) amplitudes from Cz and Pz electrodes (as in Panel A). **Panel C**: Scalp t-maps show IA>CA (left) and IN>CN (right) analyses in the theta band (3-7Hz) between 300-500ms (as outlined in Panel A). Significant electrodes (p<0.025, FWE-corrected with cluster-based permutation test) are marked with asterisks, marginal significance (two-tailed p<0.05, FWE-corrected) is marked with crosses.

Discussion

We examined the effect of negation on N400 amplitudes and oscillatory power and ITPC, and its dependency on two distinct sentence structures in which the negation operator appeared. One structure depicted the truth-value affecting function in categorical relations, the other structure contained semantic verb-object relations with attenuating function of the negation operator. Furthermore, we investigated a possible inhibiting role that negation word plays for the semantic activation of its following concepts.

In the categorical set, the N400 amplitude resulted in a clear interaction between truth value and negation, as shown in former studies (Dudschig et al., 2019; Fischler et al., 1983): In the affirmative conditions, false sentence endings resulted in increased negativity; for the negative conditions, true but semantically-unrelated sentence endings elicited a significant N400 increase. Thus, the amplitudes were dependent on the semantic relatedness of the target words to the preceding context. This is in line with the Two-Step-Simulation-Hypothesis (Kaup et al., 2006), in which truth-value affected by negation may not be processed in the N400 time window. Effects of semantic congruency as observed in the congruency sentences also support this N400 pattern. In both affirmative and negative sentences, semantic incongruency consistently elicited an N400.

Crucially, however, in both types of sentences, negation (*kein* vs. *ein*) affected the N400 amplitudes of the target words regardless of the semantic relatedness to the former words (For a direct comparison between congruent affirmative and negative conditions, c.f. **Figure S, Panel B** in the supplement). Thus, negation revealed a main effect without any interaction within the N400 time window. This presence of an N400 effect after negation may suggest that negation is not only reflected in later time windows than the N400 time window (Dudschig et al., 2019; Lüdtke et al., 2008; Palaz et al., 2020). Rather, the negation operator affects the semantic processing of a target word, regardless of the semantic relatedness. One explanation might be that negation makes a target word less accessible. Thus, also when the brain is not engaged in a truth-value judgement, negation seems to play a fundamental role in activating a concept (Kaup, 2001). The question then arises, whether this attenuation function also applies to accessing semantically unpredicted words. From a pragmatic perspective, one might expect that in sentences with incongruent negative sentence endings, the implausibility could be directly and fully integrated (Schiller et al., 2017). However, we also found increased negativity for *kein* vs. *ein* for incongruent (i.e. less predicted) words in the N400 time window. If the attenuating function of a negation operator had the effect of a full pragmatic integration of incongruency, this would lead to no N400 effects in these conditions. Another explanation could be that, similar to the Two-Step-Simulation-Hypothesis, pragmatic inferences indeed are not fully reflected in the N400 time window. Importantly, whereas former studies proposed either a delay in negation processing (Lüdtke et al., 2008), or provided very specific contexts in which negation processing might be facilitated (Nieuwland, 2016; Nieuwland & Kuperberg, 2008; Tian & Breheny, 2016), our results point in the direction of a more interactive way of integration. Haase et al (2019) have proposed this more hybrid view on negation processing. However, the dependence on the negation operator's function is a novel finding of the current study.

Our oscillatory power and ITPC results in the theta band provide further insights into this view. Across both experiments, we observed increased theta power for semantically unrelated target words (FA>TA and IA>CA). Thus, our findings corroborate prior research on the potential functional relevance of the theta band during semantic processing (Hagoort, 2004; Pu et al., 2020). However, remarkably, both the theta power and ITPC were affected by negation in a nuanced manner in two different types of sentences: Whereas the theta power increase for false and incongruent target words was found only in affirmative conditions, in negative sentences, false and true / congruent and incongruent sentence endings resulted in no differences. Furthermore, significant theta power effects were found in later stages than the ERP effects. This suggests firstly that theta band power inherits a distinct role in sentence processing, and semantic integration might not be conclusively finished as soon as the N400 component attenuates. Furthermore, negation affects this (later) integration.

As increased theta band power has been related to higher retrieval costs (Hald et al., 2006; Prystauka & Lewis, 2019 for a review; Strauß, 2015), our results suggest that sentence negation can modulate these costs, which possibly leads to a more fine-grained model of negation processing. One explanation might be that a sentence's polarity (in this case affirmation) leads to a constraint of sentences (Rommers et al., 2017). Then, negation affects the expectancy of target words and leads to a less strong expectation violation for false or incongruent sentence endings after a negation word had to be processed. Another explanation might be the inhibitory nature of negation, which was formerly researched in the framework of embodied cognition. Here, linguistic negation was found to interact with response inhibition in a Go/NoGo task (de Vega et al., 2016; Beltrán et al., 2019). However, neither was a main effect of linguistic polarity negation found independently, nor was the linguistic context controlled in terms of target word predictability. Nevertheless, our data suggest that the negation operator inherits inhibiting nature also in a mere linguistically controlled context, but in an interactive nature with its function in a context of related or unrelated concepts. When a negation operator is relevant for the truth-value, both factors interact in contributing to higher semantic retrieval effort of a target word (Fischler et al., 1983). When negation is not truth-value relevant, it nevertheless does affect the semantic retrieval of a target concept (see also the supplement for direct negation comparisons that are in line with this interpretation). Thus, negation is considered interactively processed in both sentence types, depending on the differential degree of predictability and integration. This interactive nature of negation processing accord with empirical findings and theoretical proposals for sentence processing (Nieuwland et al., 2020).

In contrast to the theta power results, on the other hand, theta ITPC were generally affected by semantic relatedness, in a way similar to the N400. This clearly contrasts the ERP/theta-ITPC results to the role of theta band power, and indicates that ERP and ITPC effects inherit similar functions in sentence processing. The absence of a strong theta power effect in the presence of N400 effects (e.g. in incongruent sentence endings after negation) has been discussed e.g. in Rommers & Federmeier (2018), where lower theta band power was observed along with higher phase correlation after unpredictable words, compared to predictable words. Here, for predictable words, a decreased attention might be conceivable, which, in turn also decreases ITPC effects (c.f. Joon Kim et al., 2007; Rommers & Federmeier, 2018). At this point, the task of our experiment is relevant to mention. The subjects were instructed to detect the truth value / plausibility of the sentences, which might have influenced the attention on the target words for task detection. We consider this as a potential limitation, and further research needs to investigate how differential tasks might have an impact on the effects of negation, as reported in Wiswede et al. (2013) and Herbert & Kissler (2014).

Altogether, our data showed that the integration of negation is already seen in the N400 amplitude level, and that negation potentially inherits an inhibiting nature affecting the semantic retrieval costs of target words. Furthermore, we saw that a negation operator might be a relevant contributor to increased processing costs, regardless of the semantic relatedness of content words. In categorical sentences with a truth-value rendering function of negation, the detection of the trueness of a sentence is considered interactively. However, importantly, negation itself also causes a main effect when it attenuates the activation of a concept. Thus, our results are in line with the findings suggesting that the processing of linguistic negation is interactive, i.e., dependent to certain extent on the embedded sentence context (Lüdtke et al., 2008; Nieuwland, 2016; Nieuwland & Kuperberg, 2008; Spychalska et al., n.d.; Tian & Breheny, 2016).

To conclude, we disentangled sentence processing of truth-value, semantic congruency and negation, reflected in N400, theta power and ITPC effects. As expected, negation plays a crucial role in semantic processing, affecting sentence processing interactively based on the surrounding context (Nieuwland, 2016). We found that theta band power played a crucial role in the semantic processing of target words and that negation significantly modulated the integration costs of them. Importantly, we found that this was the case not only in sentences where a negation operator rendered the truth value of a sentence, but also in sentences where the negation operator inherits an attenuating function, which is a form of negation that is often used in daily communication. To our knowledge, this is a novel finding and highlights a potential inhibiting role of negation during sentence processing. Further research needs to replicate this potential role of negation, as well as the possible interaction between ERP and theta ITPC effects.

Conflict of interests

The authors declare no conflicts of interest.

Author Contributions

Johanna Sommer and Dr. Yifei He conceived the experiment. Johanna Sommer acquired and analyzed the data, and wrote the manuscript. Dr. Yifei He supervised the analysis. Prof. Dr. Silvia Hansen-Schirra and Prof. Dr. Arne Nagels acquired the funding. All authors contributed to the revision and approved the manuscript.

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