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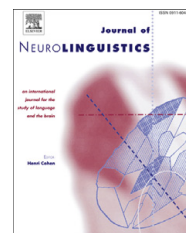
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Brain responses to syntax constrained by time-driven implicit prosodic phrases



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ABSTRACT

Previous research suggests that time-based working memory limits of 2–3 s constrain the integration of verbal information, and that speakers tend to parse sentences into prosodic phrases that do not extend beyond this time window. The present study used Event-Related Potentials (ERPs) to investigate how time-driven implicit prosodic phrasing influences the syntactic processing of embedded clauses. Participants read Swedish sentences in which the first embedded clause had a subordinate, main or neutral clause structure cued by the position of the sentence adverb. The presentation rate was manipulated so that either one or two clauses were read within 2.7 s. When the 2.7 s time limit was reached before the onset of the embedded clause, the sentence adverb indicating subordinate clause structure elicited a posterior negativity and a late positivity. These effects were interpreted to reflect the detection of unexpected word order, followed by the revision of the anticipated main clause structure. A positive shift that correlated with individual working memory span was also seen at the clause-final word after 2.7 s, possibly indicating closure of an implicit prosodic phrase. These results suggest that prosodic phrasing was influenced by time-based working memory limits, which in turn affected syntactic analysis: readers were more likely to interpret an embedded clause as a main clause if it could be associated with the beginning of a new prosodic phrase.

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1. Introduction

Baddeley (1997) proposed a 2–3 s long time limit constraining the duration of information that can be held in verbal working memory. This temporal limitation might derive from a more general neurocognitive principle that underlies the processing of sensory information. Based on the observation of a wide range of perceptual and production patterns such as movement sequencing and the segmentation of speech, Pöppel (1997) suggested that a temporal sequence within an interval of 3 s can be integrated and preserved as a unit. A specific implication for language processing is that there is a temporal constraint on the length of processing frames within which linguistic forms are sequenced and processed. According to Sachs (1974), formal aspects of discourse need to be recoded into longer-lasting (propositional) semantic representations while rapidly decaying formal (e.g. phonological, morphological and syntactic information) traces are still active in working memory. Prosodic phrasing seems to be adapted to these time-based working memory limits: Vollrath, Kazenwadel, and Krüger (1992) reported a median length of 2.6 s for intonation phrases in German conversations and Roll, Lindgren, Alter, and Horne (2012) showed that readers parsed utterances into 2.7 s long implicit prosodic phrases. Prosodic phrasing in turn has been observed to influence syntactic processing: embedded clauses following explicit prosodic phrase boundaries increased listeners' expectation of main clause structure (Roll, Horne, & Lindgren, 2009, 2011). The present study aims to extend these findings and investigate how implicit prosodic phrasing affects the parsing of embedded clauses as a result of time constraints on working memory. We manipulated the rate with which sentences were presented in order to vary the number of clauses that were read within the 2–3 s limit assumed to correspond to the duration of a prosodic phrase. Using event-related brain potentials (ERP), we tested whether readers have a tendency to analyze embedded clauses whose onset is beyond the assumed time window of about 3 s, i.e. at the beginning of a new prosodic phrase, as main clauses if no other cues are given indicating either subordinate or main clause interpretation.

1.1. Time-based constraints on working memory

In short-term recall of word sequences, performance has been found to decline as the temporal duration of words increases, indicating a time limit on the activation of verbal material (Baddeley, Thomson, & Buchanan, 1975). Based on the observed relationship between participants' reading rate and the amount of material they could recall, Baddeley et al. (1975) suggested that memory traces encoded in a temporary verbal memory store decay within 2 s unless maintained through rehearsal. A similar average interval of 2–3 s has been proposed to delimit the 'subjective present', during which successive events may be perceived as taking place at the same moment in time (Fraisse, 1984; Pöppel, 1997).

Alternative approaches to working memory that do not postulate distinct storage systems emphasize that both long-term and short-term memory processes rely on the same set of representations and retrieval mechanisms (e.g. Anderson et al., 2004; Cowan, 2000; Jonides et al., 2008; McElree, 2001). These accounts generally distinguish between a highly restricted focal state of memory defined by the number of chunks it can hold and a practically unlimited non-focal state. Everything outside of the focus of attention needs to be retrieved for processing; nevertheless, a set of representations, such as the most recently perceived items in non-focal state, may be temporarily more accessible due to a momentarily heightened level of activation (Jonides et al., 2008). Neural network models of verbal working memory suggest that these activated representations outside of the focus undergo trace decay (Jones & Polk, 2002; Lansner, Marklund, Sikström, & Nilsson, 2013). Accordingly, temporal decay in activation levels, together with similarity-based interference, are among the main factors that have been proposed to affect information retrieval during language comprehension: memory representations are assumed to receive activation boosts at moments of retrieval or when items with similar features are accessed, and these enhanced states of activation are followed by rapid time-based decay (Lewis & Vasishth, 2005; Vasishth & Lewis, 2006). Thus, the notion of temporal constraints on integration processes during language comprehension is compatible with unitary conceptions of memory since such limitations may derive from the fading of representations constituting the most recently perceived items that have been removed from a focal state. A 2–3 s long time

window suggested by a range of observations (Baddeley et al. 1975; Roll, Gosselke, Lindgren, & Horne, 2013; Roll et al., 2012; Vollrath et al., 1992) could be assumed to capture an adaptation to temporal tendencies emerging from the fluctuation of activation levels above a certain baseline. A rich representation of items perceived within this time interval may be available for rapid retrieval in a way that effectively facilitates integration into coherent units during language processing.

1.2. Timing constraints and language processing

A previous neurophysiological study on agreement processing has provided support for the existence of a 2–3 s long timing constraint on the integration of formal information in sentence processing. Thus, Roll et al. (2013) found that morphosyntactic agreement violations elicited different brain responses when the temporal distance between the disagreeing words exceeded 3 s as compared to the processing of mismatching agreement features appearing within a 2.5 s window. The change in the ERP effect was characterized by a shift from left- to right-lateralization suggesting that readers relied on the propositional content of sentences and made use of pragmatic inference to establish agreement at time-periods over 3 s when grammatical forms were no longer activated in short-term memory.

The assumed 2–3 s window can be thought of as an underlying prosodic structure, which provides the basic framework for integrating phonological, semantic and syntactic information during language processing (Shattuck-Hufnagel, 2000). Roll et al. (2012) investigated the idea that the optimal maximal length of prosodic phrases reflects this assumed underlying prosodic structure characterized by a temporal interval of approximately 2–3 s. Thus, language users might tend to close prosodic phrases as the timing limit is approached since the integration of words into coherent processing units should become increasingly difficult when memory traces have started to fade away in working memory.

According to Fodor's (2002) Implicit Prosody Hypothesis, a prosodic representation of a sentence is activated during silent reading and, therefore, working memory constraints should influence the placement of prosodic boundaries even during the processing of written language. Based on a pre-test measuring speech rate, Roll et al. (2012) estimated the optimal duration of phrases to be around 2.7 s. Sentences consisting of three clauses (see example (1), syntactic clause boundaries [] are indicated) were shown at three different presentation rates so that participants read one, two or three clauses within the 2.7 s time window.

(1) [Martin klipper gärna gräset] [så det är kort] [när han har tid]

'[Martin cuts delightedly the-grass] [so it is short] [when he has time]'

Readers' ERP responses displayed an increased Closure Positive Shift (CPS) every 2.7 s when a clause-final word was reached. Thus, at fast presentation rate, where all three clauses in test sentences were read within 2.7 s, a CPS was observed only at the final word of the third clause (*tid* 'time'), whereas at the slowest presentation rate of 2.7 s per clause, all three clause-final words (*gräset* 'the-grass', *kort* 'short', *tid* 'time') triggered an increased positivity.

The CPS, a positive shift typically most prominent at centroparietal sites, has been previously found to reflect the processing of prosodic phrase boundaries in speech (Steinhauer, Alter, & Friederici, 1999) and in silent reading (at commas, Steinhauer, 2003; Steinhauer & Friederici, 2001). The results in Roll et al. (2012) seem to indicate that whenever a clause was completed around the assumed 2–3 s limit, readers closed the currently open implicit prosodic phrase. No such effect was obtained for the control sentences in which the word appearing at 2.7 s from clause-onset was in pre-final position. Furthermore, control clauses with a duration greater than 3 s were found to generate increased working memory load in participants with relatively low working memory span, presumably as a result of exceeding the temporal integration window.

Roll et al.'s (2012) study demonstrated that implicit prosodic phrases characterized by an optimal length of 2.7 s can include one or more clauses. It is not clear, however, how the interpretation of clauses in complex sentences is influenced if one versus several clauses are contained in a single prosodic phrase. Previous results summarized in the next section point to a specific interaction between prosodic phrasing and syntactic parsing of clauses: the presence or absence of prosodic boundaries modulates listeners' expectations concerning main or subordinate clause status.

1.3. Prosodic phrasing and syntactic processing

Prosodic phrasing has been shown to influence parsing decisions and potentially even reverse initial syntactic parsing preferences (Steinhauer et al., 1999). For instance, the presence of explicit prosodic boundaries signaling that the upcoming clause forms a separate prosodic phrase was found to increase listeners' expectation of main clause structure (Roll & Horne, 2011; Roll et al., 2009, 2011). Words that cued a syntactic structure inconsistent with the initial analysis, such as adverbs associated with the preceding clause, elicited a negativity followed by a late positivity in the ERP signal (Roll & Horne, 2011). The negativity was suggested to reflect violation of word order rules as a result of encountering an adverb in a position where a main clause analysis would require a verb to appear. The following positivity was interpreted as a P600 effect associated with the difficulty of integrating the adverb in the unexpected syntactic position. Conversely, when explicit prosodic cues that signaled closure of the previous clause were completely absent, a new main clause structure was less expected as indicated by a P600 effect for this construction (Roll & Horne, 2011).

2. Current study

The results of Roll et al. (2012) suggest that there are time-based constraints on the length of implicit prosodic phrases possibly deriving from working memory limitations. Furthermore, the initial interpretation of an embedded structure as a main or subordinate clause is influenced by the presence versus absence of explicit prosodic boundaries (Roll & Horne, 2011; Roll et al., 2009, 2011). It still remains to be explored, however, whether implicit prosodic phrasing constrained by the optimal length of temporal integration units modulates expectations regarding the status of embedded clauses. During the processing of written language, the time it takes to read clauses can vary due to a range of factors such as the number and length of words in a given clause. Even though readers may relatively freely adjust their reading rate, it is reasonable to assume that the number of clauses read within 2–3 s will normally show some variation, which may have specific consequences for syntactic processing. However, manipulating the length of sentences by including extra material would introduce confounding factors in the form of interference effects or increased working memory load, making it impossible to isolate the role of time constraints. Hence, in the present study, instead of changing the amount of interpolated material, we varied the rate with which participants read the exact same sentences. We tested whether readers would have a tendency to assign words read 2.7 s after the beginning of the sentence to a new prosodic phrase associated with a new main clause.

The main or subordinate status of embedded clauses can be cued by the position of sentence adverbs in Swedish. Variations in Swedish word order patterning thus provide the possibility to explore readers' expectations as regards syntactic interpretation of embedded clauses. Swedish main clauses are characterized by a S-V-SAdv (subject-verb-sentence adverb) word order while subordinate clauses have a S-SAdv-V word order. Accordingly, a sentence adverb such as *inte* 'not' follows the verb in main clauses but appears in preverbal position in subordinate clauses. Further, the clause-initial word *så* may introduce either a subordinate or a main clause, with the meaning 'so that' as a subordinating conjunction and 'so' as a coordinating conjunction. In *så*-clauses, therefore, word orders with both preverbal and postverbal sentence adverbs are grammatically correct, even though one configuration might be unexpected relative to the other if it mismatches the prediction made by the reader before encountering *så*.

Specific ERP-responses have been reported for the Swedish sentence adverb *inte* 'not' appearing in an unexpected position: Roll, Horne, and Lindgren (2007) observed a posterior negativity between 175 and 300 ms for *inte* 'not' incorrectly following a non-pronominal indefinite NP, instead of preceding the NP in the grammatically correct position. The obtained effect was suggested to be related to the so-called 'scrambling negativity', which was first observed in German for NPs that had been moved to a position in front of the subject, creating correct but non-canonical argument orders (Rösler, Pechmann, Streb, Röder, & Hennighausen, 1998; Schlesewsky, Bornkessel, & Frisch, 2003). Schlesewsky et al. (2003) interpreted the effect as reflecting the mismatch between an expected syntactic position and the features of the element actually encountered. In Rösler et al. (1998), the scrambled NP elicited a left-anterior negativity around 300–450 ms; however, a number of subsequent studies on scrambling

have reported negativities that displayed a centro-parietal distribution (Bornkessel, Schlesewsky, & Friederici, 2002, 2003; Wolff, Schlesewsky, Hirotsani, & Bornkessel-Schlesewsky, 2008). Another possibility is that the sentence adverb violating grammatical word order gave rise to a visual Mismatch Negativity (MMN) effect. Previously, MMN effects have been obtained for syntactic manipulations, which involved the occasional presentation of ungrammatical personal pronoun – verb combinations in a sequence of well-formed phrases (Pulvermüller & Shtyrov, 2003; Shtyrov, Pulvermüller, Näätänen, & Ilmoniemi, 2003). Pulvermüller and Shtyrov (2003) interpreted these findings in terms of ‘neural sequence detectors’ connecting the representations of word categories that form grammatically correct strings. These connections mediate priming effects reducing the MMN for word combinations that follow syntactic rules, whereas words in ungrammatical sequences are unprimed and produce larger brain responses. The MMN has also been observed for the visual presentation of linguistic material, in which case the negativity elicited by the deviant stimulus had a posterior distribution (Shtyrov, Goryainova, Tugin, Ossadtchi, & Shestakova, 2013).

2.1. Test material

The present study investigated the processing of visually presented Swedish sentences consisting of three clauses. Table 1 shows example sentences for each test condition. The second clause was always introduced by the ambiguous word *så* (‘so’/‘so that’), and contained either the sentence adverb *inte* ‘not’ or a VP adverb (*mindre* ‘less’ or *sällan* ‘rarely’). The sentence adverb appeared either before the verb, cueing subordinate clause word order (examples 1–2), or after the verb signaling main clause structure (examples 3–4). Embedded clauses with a VP adverb instead of a sentence adverb are neutral with regard to their syntactic status, since the adverb always follows the verb (examples 5–6). In order to vary the temporal duration of the clauses while keeping the number of words constant, test sentences were presented word by word at two different presentation rates. At slow presentation rate (0.675 s/word) each clause took 2.7 s to read, while at fast presentation rate (0.337 s/word) 2.7 s was not reached until the end of the second clause.

We predicted that the embedded clause introduced by *så* would initially be parsed differently depending on the presentation rate, and that variations in readers’ ERP responses to the sentence adverb *inte* ‘not’ in different positions would provide clues to readers’ expectations concerning the syntactic structure of the embedded clause. At slow rate, the readers would be expected to close the prosodic phrase at the end of the first clause (after *fönstret* ‘the-window’ in example 2, 4 and 6), since it is reached towards the end of the 2.7 s long interval (Roll et al. 2012). Based on previous findings that prosodic breaks increase the activation of main clause word order (Roll & Horne, 2011; Roll et al., 2009, 2011), we assumed that readers would be more prepared for a main clause reading of the *så*-clause

Table 1

Example sentences for each of the six experimental conditions. Syntactic boundaries [] and assumed prosodic phrase boundaries () are indicated.

Condition		Example sentence
Subordinate clause (SC)		
Fast	(1)	([Petter stänger alltid fönstret] _{SC} så han inte fryser]) när det är kallt. ‘Petter closes always the-window so he not freezes when it is cold.’
Slow	(2)	([Petter stänger alltid fönstret])(_{SC} så han inte fryser]) när det är kallt. ‘Petter closes always the-window so he not freezes when it is cold.’
Main clause (MC)		
Fast	(3)	([Petter stänger alltid fönstret] _{MC} så han fryser inte]) när det är kallt. ‘Petter closes always the-window so he freezes not when it is cold.’
Slow	(4)	([Petter stänger alltid fönstret])(_{MC} så han fryser inte]) när det är kallt. ‘Petter closes always the-window so he freezes not when it is cold.’
Neutral clause (NC)		
Fast	(5)	([Petter stänger alltid fönstret][så han fryser mindre]) när det är kallt. ‘Petter closes always the-window so he freezes less when it is cold.’
Slow	(6)	([Petter stänger alltid fönstret])([så han fryser mindre]) när det är kallt. ‘Petter closes always the-window so he freezes less when it is cold.’

after 2.7 s. In this case, encountering a sentence adverb in the preverbal position (*inte* ‘not’ in example 2) after *så* would be unexpected. The ERP response elicited by *inte* ‘not’ was predicted to be an enhanced negativity, similar to the scrambling negativity that has been observed in German for correct but non-canonical word orders. However, sentence adverbs in unexpected positions might yield ERP responses that differ in certain respects from effects observed for full NPs. For instance, neuroimaging studies suggest that the processing of non-pronominal scrambled objects are influenced by factors such as thematic role prominence, the preferred ordering of animate and inanimate arguments, and canonical subject-object order (Bornkessel, Zysset, Friederici, von Cramon, & Schlesewsky, 2005; Grewe et al., 2005, 2006). Features such as thematic role and animacy are relevant for determining the relative ordering of full NP arguments but are not present in negators. In line with the results of Roll et al. (2007), the negativity for *inte* ‘not’ might therefore have an earlier latency, appearing before the time range of the N400 associated with thematic and semantic processing (Friederici, 2011). The negativity could be followed by a P600 reflecting revision of the anticipated main clause structure into a subordinate one.

At fast presentation rate, readers were predicted to associate the first two clauses with a single prosodic phrase. In spoken language processing, the absence of sentence-internal prosodic boundaries has been found to decrease the expectation of an embedded main clause structure (Roll & Horne, 2011). Thus, we predicted that in read speech, where word presentation rate could influence prosodic phrasing, main clause word order with *inte* ‘not’ in postverbal position (as in example 3) would be less expected at a fast reading rate. At fast presentation rate, therefore, it was the postverbal *inte* ‘not’ that was predicted to yield a posterior negativity and possibly a P600. Furthermore, at both presentation rates an N400 effect was expected for the control word: *inte* ‘not’ was compared to a verb (*fryser* ‘freezes’) in the neutral conditions and closed-class words tend to elicit smaller N400s than open-class words (Müntz et al., 2001).

The hypotheses were tested by comparing responses evoked by sentence adverbs to items in the corresponding sentential positions in neutral *så*-clauses. As this procedure involved contrasting items of different word classes (adverb versus verb in the subordinate clause conditions), the same comparisons were always made at both presentation rates. ERP effects specific to slow or fast rates are unlikely to derive from word class differences in the target position since such differences should conceivably be present regardless of the presentation rate. A potential problem inherent to comparing different presentation rates within the same analysis relates to the way the two conditions diverge during the time range of the N400 component. At fast rate, the next word is presented at 337 ms following target-onset, whereas at slow presentation rate, readers are exposed to the same target item for another 338 ms. Importantly, variations involving the N400 do not have any critical ramifications for the hypotheses. Moreover, the time range of the negativity (175–300 ms) that is predicted as a response for unexpected word orders, and which thus constitutes the main concern of this study, precedes the point after which the conditions begin to differ.

In order to establish whether the observed parsing preferences derived from different prosodic phrasings at the different presentation rates, brain responses to clause-final words (*fönstret* ‘the-window’ in example 5–6) were compared to effects elicited by pre-final items (*fryser* ‘freezes’ in example 5–6) in neutral clauses. As noted earlier, readers were predicted to close the current prosodic phrase already at the end of the first clause (at *fönstret* ‘the-window’) when the presentation rate was slow (see Table 1). This would be reflected in a CPS effect in comparison with the third word of the second clause (*fryser* ‘freezes’) where no prosodic phrase boundary would be expected, as neither the end of the clause nor the time limit of 2.7 s would have been reached. At fast presentation rate, where the first prosodic boundary would be expected only at the end of the second clause, i.e. after both *fönstret* ‘the-window’ and *fryser* ‘freezes’, the comparison of the same words was not predicted to reveal a CPS effect.

It was hypothesized that readers would close prosodic phrases at around 2.7 s as a result of working memory limitations. Individuals with a high working memory span might, however, be able to process phrases that span over longer time intervals. This individual variation might be seen in a correlation between working memory span and the CPS effect predicted for the clause-final word at slow presentation rate. In order to test this assumption, participants’ working memory span was measured using the Automated Running Span task (Broadway & Engle, 2010).

3. Method

3.1. Participants

Twenty-two right-handed Swedish native-speakers participated (11 women). Mean age was 25.5 years, $SD = 5.40$.

3.2. Material

Example sentences for the test conditions are shown in Table 1. Each sentence consisted of three 4-word clauses made up of monosyllabic and disyllabic words. The third clause was always an adverbial clause introduced by *när* 'when', and it was added to ensure that the critical word never appeared in sentence-final position. In the embedded *så*-clause of the subordinate clause conditions (SC), the sentence adverb *inte* 'not' occurred before the verb signaling subordinate clause structure. In the main clause condition (MC), *inte* 'not' followed the verb creating main clause word order. The *så*-clauses of the neutral clause conditions (NC) were neutral concerning the embedded clause status since they contained a VP adverb instead of a sentence adverb. The VP adverb was *sällan* 'rarely' in half of the sentences and *mindre* 'less' in the other half, as they were semantically appropriate in the sentence context. Each test sentence (40 per condition) and 80 unrelated well-formed filler sentences were shown at two different presentation rates resulting in a total of 400 trials.

3.3. Procedure

Sentences were displayed one word at a time, in white font against a black background at the center of a computer screen. Stimulus onset asynchrony (SOA) was 337 ms at fast presentation rate and 675 ms at slow presentation rate, both including a 50 ms interstimulus interval of blank screen. Sentences were presented in a pseudo-randomized order, distributed over 8 blocks, and 20% of the trials were followed by comprehension questions, which the participants answered by pressing one of two keys (1 = Yes, 2 = No). The presentation rates were randomized within each block.

3.4. EEG recordings

EEG was recorded from 25 electrodes mounted on an elastic cap (Easycap) using Synamps amplifiers and Neuroscan Acquire software. Recording reference was a central cap-mounted electrode. Offline, reference was re-calculated to the average of the right and left mastoids. The electrooculogram was recorded by electrodes placed above and below the left eye and at the outer canthi of both eyes. Data were sampled at a rate of 250 Hz, and the on-line bandpass filter was set at 0.05–70 Hz. Electrode impedances were kept below 5 k Ω .

3.5. Data analysis

Offline, the EEG was filtered with 30 Hz low pass and was segmented into 1000 ms epochs following the onset of the critical words. Ocular artifacts were corrected for by using Independent Component Analysis (Jung et al., 2000). EEG segments were removed from analysis if the signal amplitude exceeded $\pm 100 \mu V$ ($M = 3.48$, $SD = 1.65$). A low-pass filter of 12 Hz was used for presentation only.

3.5.1. Early negativity, N400 and late positivity related to main clause/subordinate clause status

Two separate analyses were conducted on the EEG data. The first analysis focused on the effects of the sentence adverb *inte* 'not' in the SC and the MC conditions as compared to items in corresponding sentential positions in the NC conditions. Mean amplitudes were computed relative to a 200 ms baseline preceding the critical words. For the comparison between the SC and NC conditions, the ERPs were time-locked to the second word of the *så*-clause (*inte* in SC and the verb in NC). For the MC versus NC analysis, ERPs were calculated from the onset of the third word of the *så*-clause (*inte* in MC and the VP adverb *sällan* 'rarely' or *mindre* 'less' in NC). In this way, each comparison involved only sentences

that were identical up to the critical word. Three time windows were created based on previous literature and visual inspection of the data: 175–300 ms for the negativity (Roll et al. 2007), 300–500 ms for the N400 effect and 850–950 ms for the late positivity. Electrodes were grouped into six regions of interest (ROIs) of two electrodes each (Fig. 1): left anterior (F7, F3), right anterior (F4, F8), left central (T7, C3), right central (C4, T8), left posterior (P7, P3), right posterior (P4, P8).

Statistical analysis was carried out separately for the following two comparisons: *inte* ‘not’ in the SC conditions vs. the verb in the corresponding sentential position in the NC conditions at both presentation rates, and *inte* ‘not’ in the MC conditions vs. the VP adverb in the NC conditions at both presentation rates. For both comparisons, repeated measures ANOVAs were conducted in each time window with the factors Rate (levels: slow, fast), Word class (levels: *inte*, verb/VP adverb), Anteriority (levels: frontal, central, posterior) and Laterality (left, right). Significant and marginal interactions were broken down first by the topographical factors and then by Rate. Greenhouse-Geisser correction was applied where relevant, and the corrected p values are reported along with original degrees of freedom.

3.5.2. CPS-effects related to alignment of clause and prosodic phrase boundaries

The second analysis involved only the items of the NC conditions to test for CPS effects at clause-final words. The ERPs were time-locked to the onset of the final word in the first clause and to the pre-final word in the second clause in the NC conditions. Thus, the two conditions differed in terms of the words immediately preceding the targets (sentence adverb versus pronoun), and a pre-stimulus baseline relative to the target onset could have possibly picked up earlier effects related to word class differences. For that reason, a 200 ms time window before sentence onset was used as the baseline. Visual inspection suggested a positive effect between 600 and 800 ms at slow presentation rate (Fig. 6) whereas at fast presentation rate, waveforms diverged around 700–900 ms, due to the N400 amplitude difference between the words that followed the critical items in these conditions (Fig. 7). As a result of this observation, a shorter time window of 600–700 ms was chosen for testing the CPS effect, instead of the 600–800 ms time range suggested by the visual inspection. Mean amplitude values were analyzed with repeated measures ANOVAs, applied separately to midline and lateral regions. Midline analysis included the factors Rate (levels: slow, fast), Word position (levels: clause-final, pre-final), and the topographical factor Electrode (levels: Fz, Cz and Pz).

4. Results

4.1. Behavioral data

Overall accuracy on the comprehension task for the six experimental conditions was 92.4% ($SD = 6.2\%$). Mean accuracy was 96.8% in SC-fast, 87.7% in SC-slow, 94.5% in MC-fast, 89.2% in MC-slow, 93.9% in NC-fast and 90% in NC-slow. A repeated measures ANOVA with the factors Clause Structure (levels: main, subordinate, neutral) and Rate (levels: slow, fast) yielded a main effect of Rate, $F(1,$

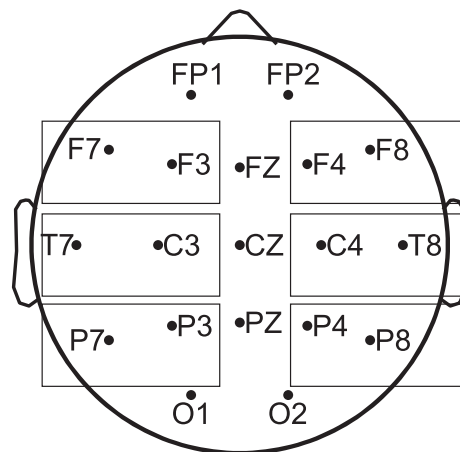


Fig. 1. Channel locations and delimited regions of interest.

21) = 15.69, $p < .001$, but no interaction between the factors Rate and Clause Structure, $F < 1$, indicating that participants were generally less accurate at answering comprehension questions when presentation rate was slow as compared to fast presentation rate.

4.2. Sentence adverb effects

4.2.1. Subordinate clause word order

Figs. 2 and 3 show the ERPs for the preverbal sentence adverb *inte* ‘not’ relative to the word in the same position in the neutral condition (the verb) at slow and fast presentation rates. The ANOVA for the 175–300 ms window resulted in a Rate \times Word class \times Ant interaction, $F(2, 42) = 5.48$, $p = .024$. Further analyses within each level of the Anteriority factor detected a Rate \times Word class interaction at posterior regions, $F(1, 21) = 7.37$, $p = .013$. Resolving the interaction showed an effect of Word class at slow presentation rate, $F(1, 21) = 6.85$, $p = .016$, which was due to an increased posterior negativity for *inte* ‘not’ as compared to the verb (Fig. 2). No effect of Word class was obtained at fast presentation rate, $F < 1$ (Fig. 3).

In the 300–500 ms time window, the ANOVA found a main effect for Word class, $F(1, 21) = 4.44$, $p = .047$, as well as Word class \times Ant interactions, $F(2, 42) = 7.37$, $p = .007$, and Word class \times Lat interactions, $F(1, 21) = 7.13$, $p = .014$, indicating that the verb elicited more negative amplitudes than *inte* ‘not’ at both presentation rates (Figs. 2 and 3). Further analysis revealed that the negativity was confined to central, $F(1, 21) = 5.05$, $p = .035$, and posterior sites, $F(1, 21) = 7.37$, $p = .013$, and the effect of Word class was significant for right hemisphere, $F(1, 21) = 7.19$, $p = .014$, but not for left hemisphere regions.

In the 850–950 ms time window a Rate \times Word class \times Lat interaction was found, $F(1, 21) = 4.92$, $p = .038$. Follow-up analysis showed a Rate \times Word class interaction over right hemisphere regions, $F(1, 21) = 4.64$, $p = .043$, where an increased positivity was present for *inte* ‘not’ as compared to the verb at

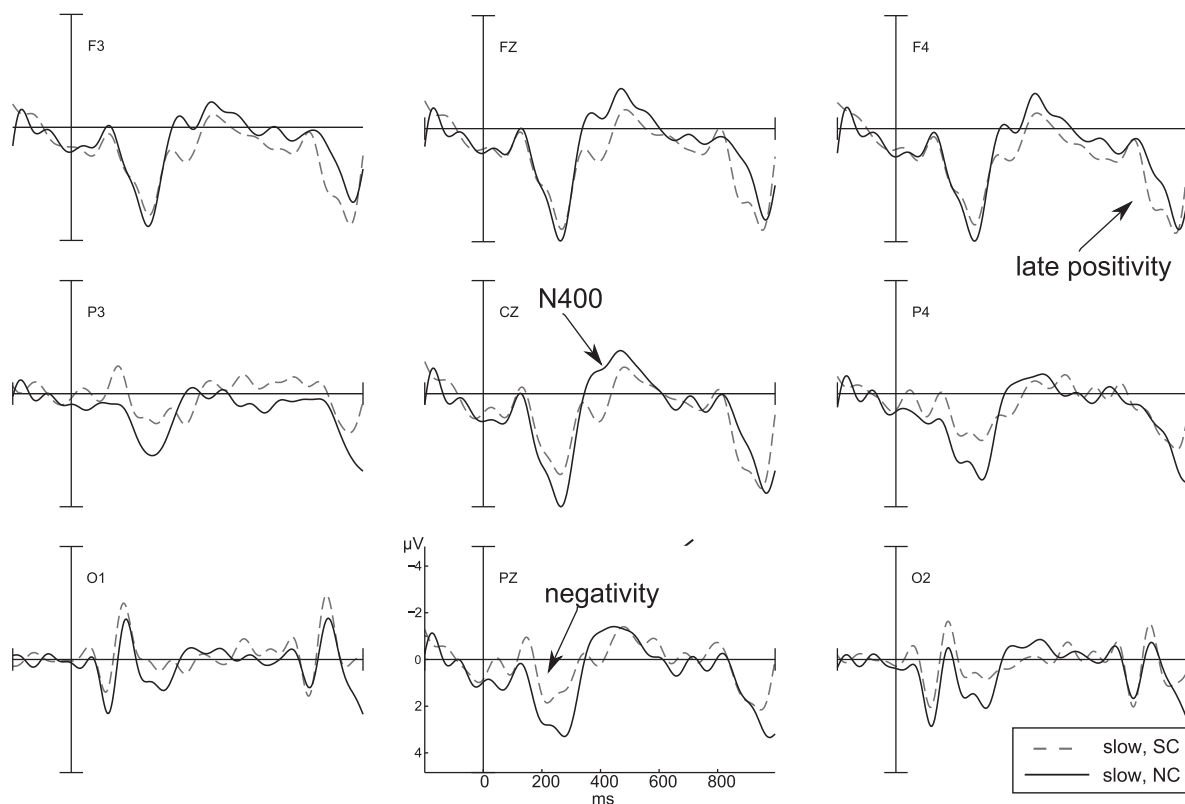


Fig. 2. ERPs at 9 selected electrodes for the target words in subordinate clauses (SC, dashed line) and neutral clauses (NC, solid line) at slow presentation rate (SC: *Petter stänger alltid fönstret så han inte fryser när ...* “Petter closes always the-window so he not freezes when ...”, NC: *Petter stänger alltid fönstret så han fryser mindre när ...* “Petter closes always the-window so he freezes less when ...”, target words are underlined). SC elicited a posterior negativity between 175 and 300 ms followed by a late positivity. Verbs (NC) produced larger N400 amplitudes than sentence adverbs (SC).

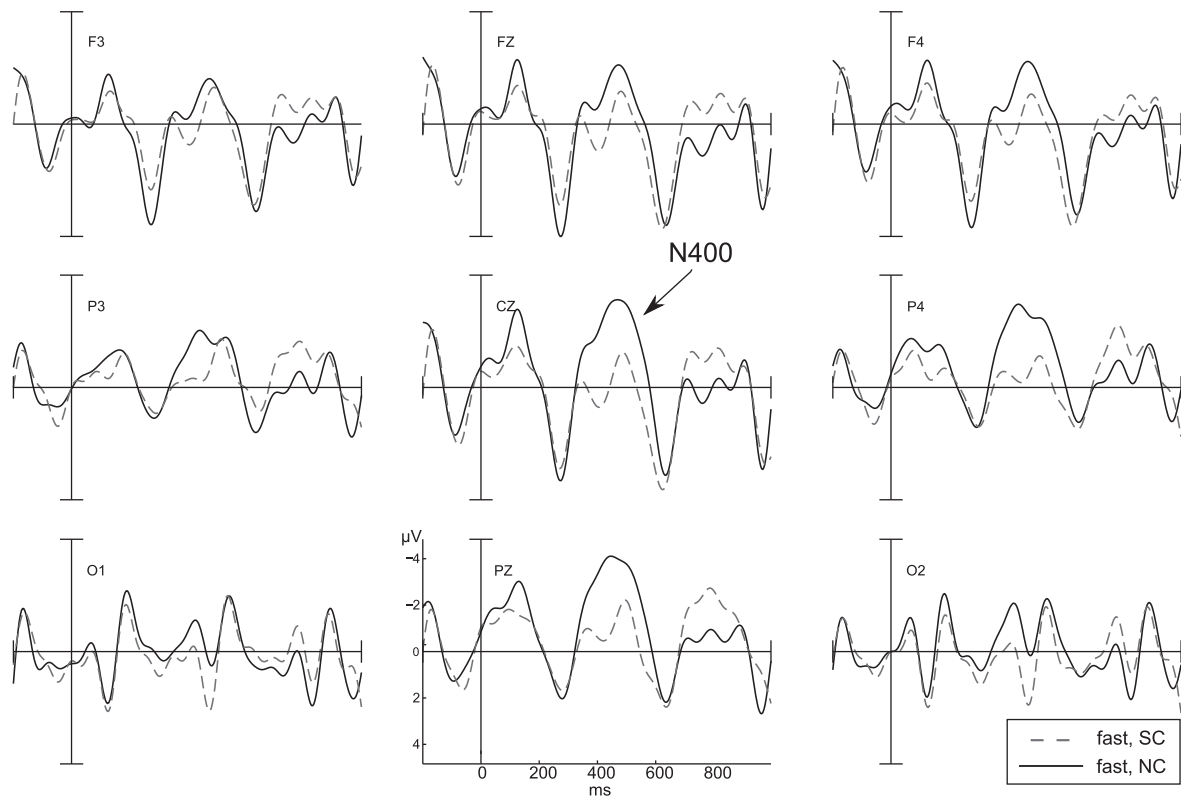


Fig. 3. ERPs at 9 selected electrodes for the target words in subordinate clauses (SC, dashed line) and neutral clauses (NC, solid line) at fast presentation rate (SC: *Petter stänger alltid fönstret så han inte fryser när ...* "Petter closes always the-window so he not freezes when ...", NC: *Petter stänger alltid fönstret så han fryser mindre när ...* "Petter closes always the-window so he freezes less when ...", target words are underlined). There is an enhanced N400 for verbs (NC) relative to sentence adverbs (SC).

slow presentation rate, $F(1, 21) = 6.90$, $p = .016$ (Fig. 2), but no effect of Word class was detected for fast presentation rate, $F < 1$. At the left hemisphere region, the interaction Rate \times Word class did not reach significance.

4.2.2. Main clause word order

ERPs for the postverbal sentence adverb *inte* 'not' were compared to ERPs for the VP adverb in the neutral condition at fast and slow presentation rates. In the 175–300 ms time window, a repeated measures ANOVA including all ROIs found no interactions involving both the Rate and the Word class factors. Separate analyses for the levels of Rate at posterior regions yielded a marginal Word class \times Lat interaction at fast presentation rate, $F(1, 21) = 3.41$, $p = .079$, which was due to *inte* 'not' being marginally more negative than the neutral adverb at the right posterior ROI, $F(1, 21) = 3.21$, $p = .088$ (Fig. 4). Analyses within the slow presentation rate did not reveal any significant or marginal differences between *inte* 'not' and the neutral adverb at posterior regions or specifically at the right posterior ROI, Word class: $F(1, 21) = 1.11$, $p = .303$ (Fig. 5).

The ANOVA for the 300–500 ms window resulted in a Rate \times Word class \times Lat interaction, $F(1, 21) = 6.60$, $p = .018$, but further analyses within each level of the Laterality factor did not reveal any significant differences.

In the 850–950 ms latency range, no interactions involving both the Rate and Word class factors were found.

4.2.3. Split half analysis

Each participant read all six sentence-versions that made up a lexical set, such as the one shown in Table 1, which could possibly have rendered sentences more and more predictable as the experiment progressed. In order to establish whether the predictability of the stimulus material influenced the main results of the study, a split half analysis was performed in the 175–300 ms time window (see

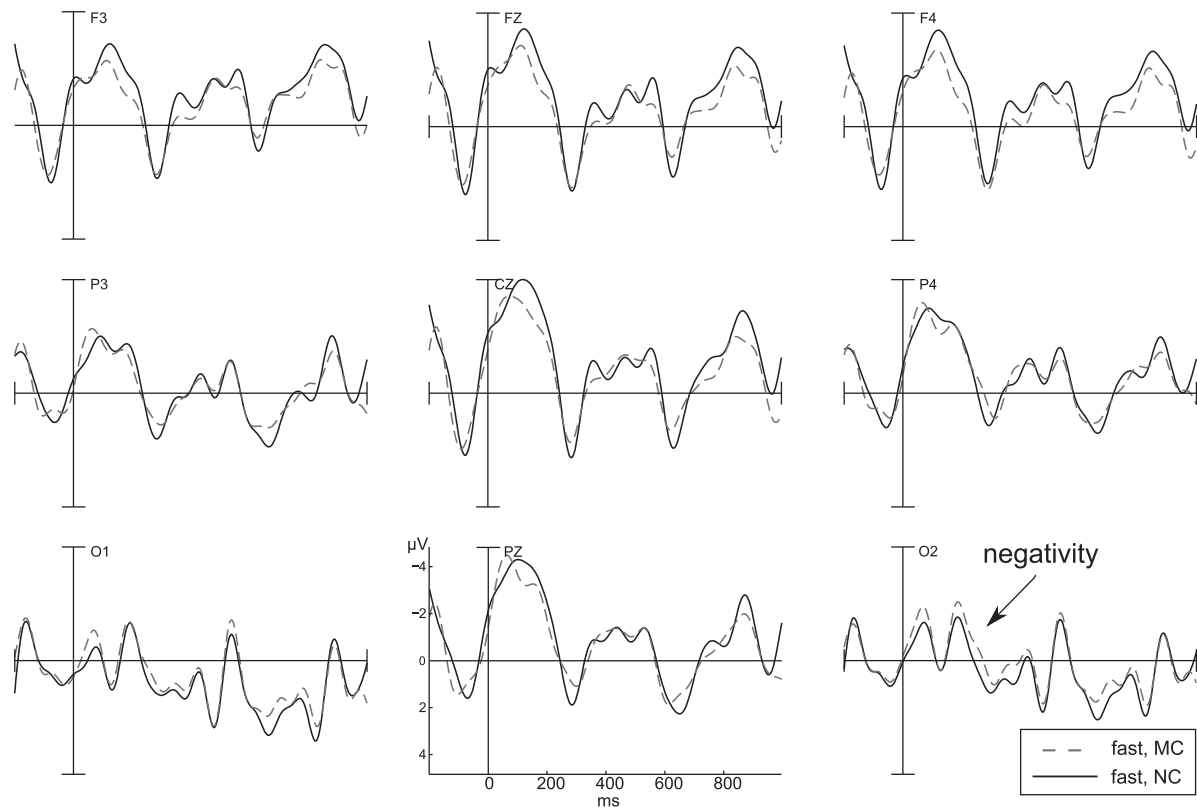


Fig. 4. ERPs at 9 selected electrodes for the target words in main clauses (MC, dashed line) and the neutral clauses (NC, solid line) at fast presentation rate (MC: *Petter stänger alltid fönstret så han fryser inte när ...* "Petter closes always the-window so he freezes not when ...", NC: *Petter stänger alltid fönstret så han fryser mindre när ...* "Petter closes always the-window so he freezes less when ...", target words are underlined). MC is more negative than NC between 175 and 300 ms in the right posterior ROI.

Supplementary Material). The ANOVAs for the first half of the experiment yielded the same results as the overall analysis: a significantly increased posterior negativity for preverbal *inte* 'not' indicating subordinate clause structure at slow presentation rate, and a marginally enhanced negativity in the Right Posterior ROI for postverbal *inte* 'not' signaling main clause word order at fast presentation rate. The second half of the experiment showed similar tendencies even though no differences between the conditions reached significance. The fact that significant results emerged earlier rather than later in the experiment suggests, therefore, that the effects obtained for *inte* 'not' in the overall analysis were not dependent on the predictability of the stimulus material.

4.3. Effects at the clause-final word

ERPs elicited by the final word (noun) of the first clause and the pre-final word (verb) of the second clause in neutral sentences are shown in **Figs. 6 and 7** for slow and fast presentation rates, respectively. An ANOVA applied to lateral sites in the 600–700 ms time window showed no interactions involving both the Rate and the Word position factors. Analysis of midline electrodes resulted in a Rate \times Word position interaction $F(1, 21) = 7.67, p = .011$. Follow-up ANOVAs within each level of the Rate factor detected a significant effect of Word position at slow presentation rate, $F(1, 21) = 5.41, p = .030$, reflecting an increased positivity for the final word of the first clause as compared to the pre-final word of the second clause (**Fig. 6**). No effect of Word position was obtained at fast presentation rate, $F(1, 21) = 2.42, p = .135$.

4.4. Working memory span and CPS

In order to determine whether there is a relationship between working memory span and the amplitude of the CPS effect, correlation analysis was performed based on participants' score on the

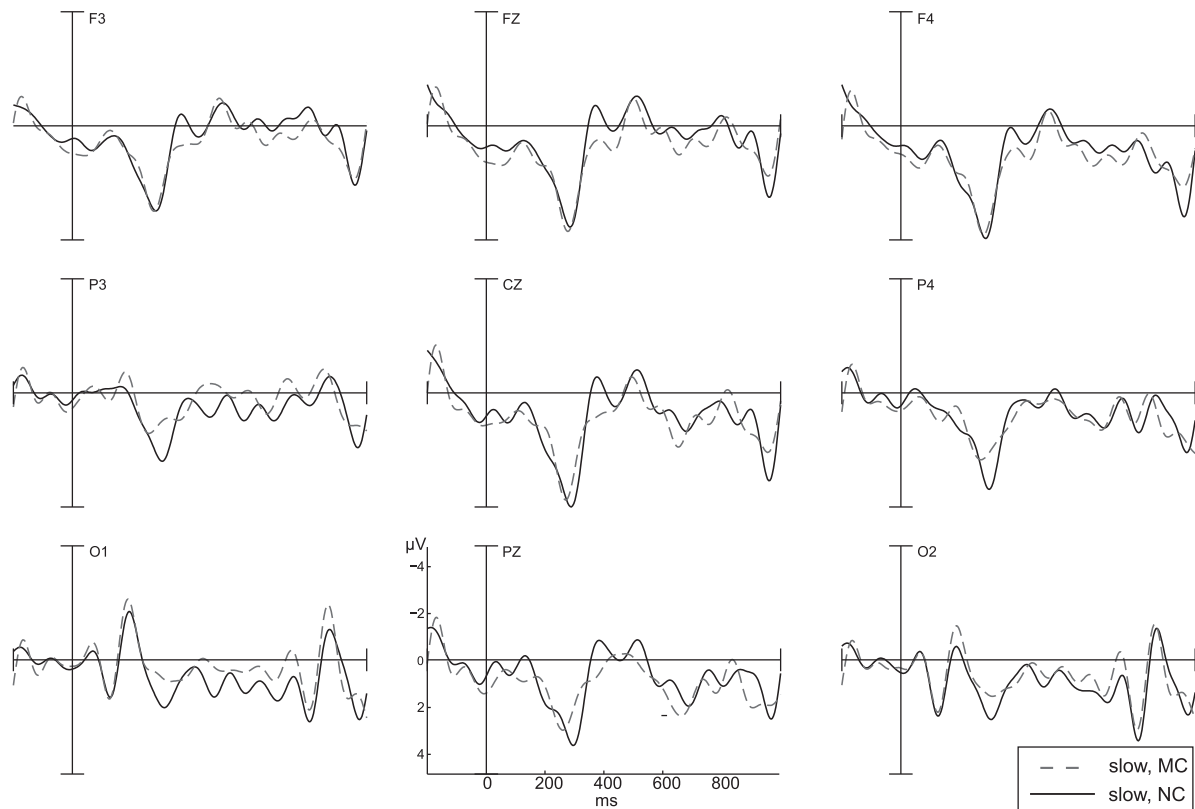


Fig. 5. ERPs at 9 selected electrodes for the target words in main clauses (MC, dashed line) and the neutral clauses (NC, solid line) at slow presentation rate (MC: *Petter stänger alltid fönstret så han fryser inte när ...* "Petter closes always the-window so he freezes not when ...", NC: *Petter stänger alltid fönstret så han fryser mindre när ...* "Petter closes always the-window so he freezes less when ...", target words are underlined). No significant differences between the neutral adverb (*mindre* 'less' or *sällan* 'rarely') and the sentence adverb *inte* 'not' were found.

Automated Running Span task and the average difference ERP amplitudes between clause-final and pre-final words at midline electrodes in the 600–700 ms time interval. The analysis revealed that the amplitude of the CPS effect was negatively correlated with working memory span, $r = -0.594$, $p = .002$, which means that greater CPS effects tended to be associated with lower working memory scores.

5. Discussion

The aim of the present study was to investigate how time-related working memory limitations influence syntactic processing through implicit prosodic phrasing. Participants read Swedish sentences in which the first embedded clause introduced by *så* 'so' had either a subordinate clause or a main clause structure depending on the preverbal vs. postverbal position of the sentence adverb *inte* 'not'. Control sentences were neutral concerning the syntactic structure of the *så*-clause. Based on previous findings, a time limit of about 2.7 s was assumed to constrain the length of implicit prosodic phrases. The presentation rate of the sentences was also varied so that 2.7 s was reached either at the end of the first clause or at the end of the second clause. ERP responses to the sentence adverb *inte* 'not' disambiguating the syntactic structure were measured to test if readers have a greater tendency to initially analyze the *så*-clause as a main clause if the preceding words form a separate prosodic phrase as opposed to a subordinate clause interpretation if the second clause can be read within the 2.7 s frame. We also recorded potentials at the final word of the first clause to see if the location of prosodic boundaries varies with respect to presentation rate.

The sentence adverb *inte* 'not' at the preverbal position elicited a posterior negativity between 175 and 300 ms at slow presentation rate. The effect had the same timing and distribution as the negativity reported in Roll et al. (2007) for negators when they appeared in an unexpected position following full

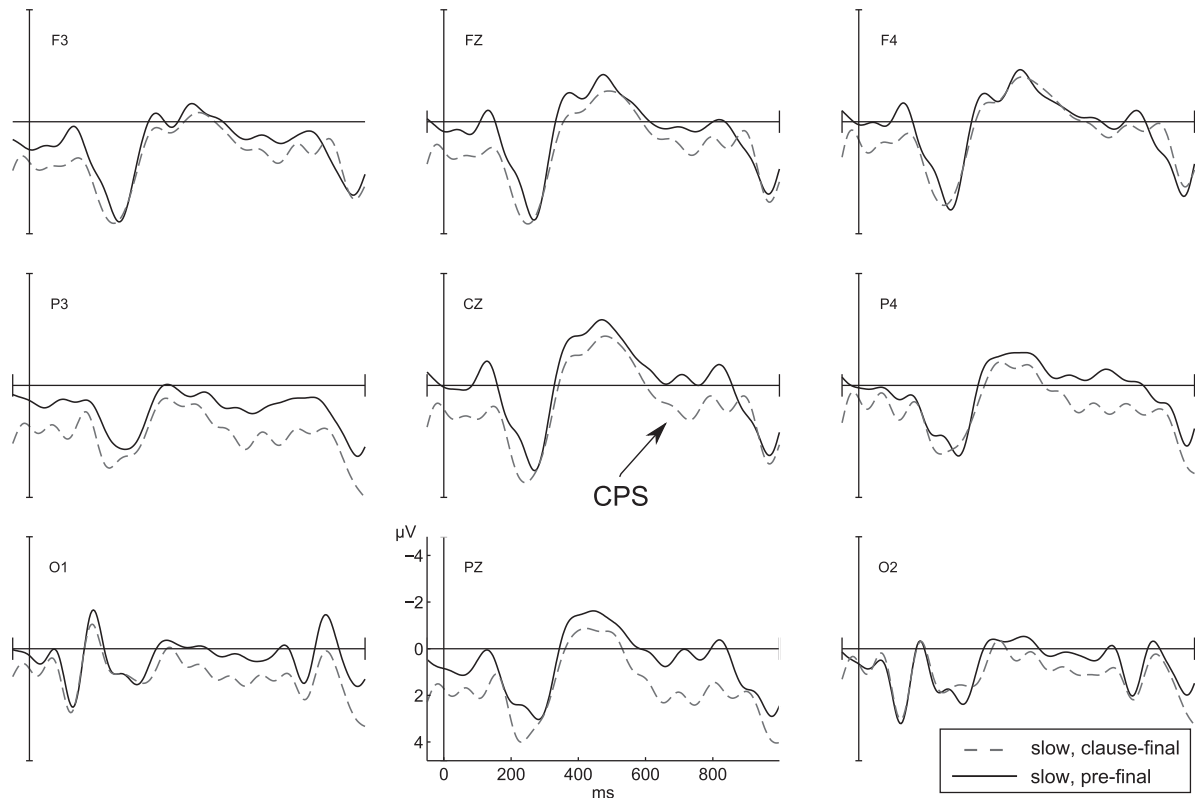


Fig. 6. ERPs at 9 selected electrodes for the final word of the first clause (dashed line) and the pre-final word of the second clause (solid line) in neutral sentences (NC) at slow presentation rate (*Petter stänger alltid fönstret så han fryser mindre när ...* “Petter closes always the-window so he freezes less when ...”, target words are underlined). A 200 ms interval preceding sentence-onset was used as the baseline. Clause-final words produced a positivity between 600 and 700 ms (CPS).

object NPs, as only pronominal object NPs may occur in front of a sentence adverb in Swedish. As mentioned above, the ERP response observed for non-canonical word orders in German scrambling structures is also an increased negativity. Thus, the negativity obtained in the present study may reflect the fact that readers found *inte* ‘not’ in the subordinate clause difficult to process, and this difficulty was potentially related to the structural position of the negator. Since the canonical Swedish main clause word order does not allow a sentence adverb to appear before the verb, the observed processing difficulty indicates that the readers seem to have initially interpreted the *så*-clause as a main clause.

An alternative explanation of the obtained negativity would be in terms of a syntactic MMN-like effect. At slow presentation rate *så* ‘so’ activated main clause word order, which requires the verb to be in the second position following the subject. Therefore, the subject primed the verb form reducing the mismatch negativity for the target word in the neutral clauses. In contrast, the sentence adverb that followed the subject in the subordinate clause was not primed at slow presentation rate, which would lead to an increased MMN.

Preverbal *inte* ‘not’ elicited a late right-lateralized positivity between 850 and 950 ms at slow rate. In light of the earlier negativity for the sentence adverb, it is possible that the effect resulted from reanalysis of the initially predicted main clause structure as a subordinate clause. Since main clause structures are interpreted as assertions whereas subordinate clauses are not (Hooper & Thompson, 1973; Roll, 2006), this would have consequences at a late processing stage where syntactic cues are integrated into a pragmatic interpretation, which is often reflected in a late posterior positivity, similar to the P600 (Bornkessel & Schlesewsky, 2006, 2008).

At both presentation rates, the verb in the neutral condition displayed an enhanced negativity relative to the preverbal *inte* ‘not’. This effect might reflect an N400 difference, in line with previous findings that open-class words tend to produce larger N400 components than closed-class words (Münte et al., 2001). Also, visual inspection suggested a positive peak for *inte* ‘not’ in the subordinate

clause conditions around 350–400 ms (see Figs. 2 and 3), which raises the possibility that the sentence adverb elicited a target-related P300 effect.¹ Consequently, the obtained negativity in the N400 time window might in fact reflect the co-occurrence of a reduced N400 and a P300 effect for the sentence adverb, which has been previously shown to create the impression of a pronounced N400 difference between two conditions (Roehm, Bornkessel-Schlesewsky, Rösler, & Schlesewsky, 2007).

As no significant effects were obtained for *inte* 'not' preceding the verb at fast presentation rate, the results suggest that readers found the subordinate clause word order unexpected only when the presentation rate was slow. Furthermore, results indicate that the temporal duration of the clauses influenced prosodic phrasing: at slow rate, the final word of the first clause in neutral sentences elicited an increased positivity over midline sites as compared to the pre-final word of the following clause.² The effect reached significance in the 600–700 ms time window that was chosen for statistical analysis, even though a somewhat longer duration of 600–800 ms was suggested by visual inspection. The positivity might be related to the CPS that has previously been observed at prosodic phrase boundaries. No such effect was present at fast presentation rate. A possible interpretation of the findings is that readers completed an implicit prosodic phrase at the end of the first clause when it was reached at around 2.7 s but not when the clause-final word was encountered well before this limit. Consequently, the *så*-clause was associated with a new prosodic phrase only at slow rate, which would explain why readers seemed to have an expectation of main clause word order in this condition (Roll & Horne, 2011; Roll et al., 2009, 2011).

The positive effect also showed a negative correlation with individual working memory span, which is in line with the suggestion that prosodic phrase length is constrained by time-based working memory limitations (Roll et al., 2012). It is possible that participants with relatively lower working memory span reached the limits on the amount of information that can be held in working memory earlier, and the need to imminently end the on-going prosodic phrase at 2.7 s is reflected in a greater positivity.

¹ P300 effects in the time range of the N400 have been reported for highly expected constituents in antonyms, idioms and collocations (Molinari & Carreiras, 2010; Roehm et al., 2007; Vespignani, Canal, Molinari, Fonda, & Cacciari, 2010). It is possible that specific characteristics of the stimulus material in the present study could have contributed to a similar effect for the sentence adverb (*inte* 'not') in the subordinate clause (SC) conditions relative to the verb in the neutral clause (NC) conditions. Apart from presentation rate, sentences in the same set differed only in terms of the form and position of the adverb in the second clause (*inte* 'not', *mindre* 'less' or *sällan* 'rarely'), and this salient variation could have drawn participants' attention to the adverb as the "target" word. In this case, encountering the string '*så* + personal pronoun' could have generated an active expectation for either a specific lexical item (*inte* 'not'), or the category of adverbs, in one of the following two positions. From this perspective, the positivity observable for *inte* 'not' in the fast-SC and slow-SC conditions might be a P300, reflecting the match between the expected item and an incoming stimulus word (Molinari & Carreiras, 2010; Roehm et al., 2007; Vespignani et al., 2010), which, in addition to the word class-related N400 effect, could have contributed to the observed ERP difference in the N400 time window.

² In the clause-final versus pre-final comparison, a difference between the ERP waveforms is already present at 0 ms at slow presentation rate (Fig. 6), which is likely to reflect an effect for the words preceding the target items (*alltid* 'always' vs. a personal pronoun *han* 'he'). Possibly, it is a P600 effect for *alltid* 'always' relative to the personal pronoun, showing up as an early increased positivity for the clause-final condition at slow rate. Reading a sentence adverb such as *alltid* 'always' would be expected to engender relatively greater syntactic processing costs, due to its central role in signaling main versus subordinate clause structure in Swedish. At fast presentation rate the same effect mostly overlaps with the N400 component associated with the target words. Supplementary Fig. 1 and Supplementary Fig. 2 in the Supplementary Material show ERPs at electrode Cz from sentence onset up until 1000 ms following the pre-final target word of the second clause in neutral sentences (*fryser* 'freezes') at both presentation rates. The waveforms at slow presentation rate display a positive deflection for *alltid* 'always' in the time-range of the P600, which is consistent with the above explanation. An alternative interpretation would be that the positivities observable for the sentence adverb *alltid* 'always' and the following clause-final word (*fryser* 'freezes') at slow presentation rate represent a single positive effect starting at the pre-final sentence adverb. The origin of such an effect would, however, be unclear. Since no similar sustained positivity is visible for the equivalent words at fast presentation rate (Supplementary Fig. 2), one possible explanation would be in terms of the temporal length of the first clause. Supplementary Fig. 1 shows that the positive deflection for the pre-final word *alltid* 'always' starts at around 2 s after sentence onset, i.e. at a time point approaching the limits of the assumed 2–3 s long temporal working memory window. From this perspective, the positivity appearing for the pre-final word as clause length exceeds 2 s, which is still present at around 3 s when the final word has been processed, might be related to the closure of the prosodic phrase in the 2–3 s interval after clause onset. However, following this line of reasoning, it would be difficult to explain why there is no corresponding positivity for the pre-final word of the following clause.

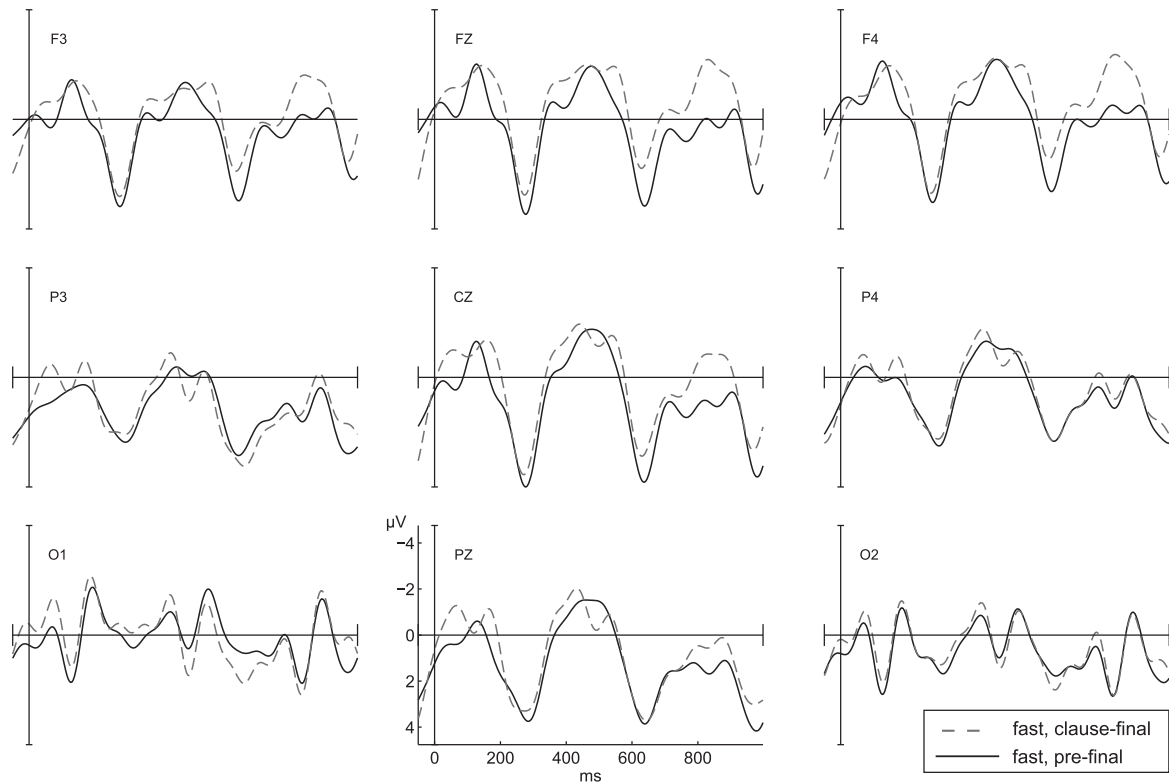


Fig. 7. ERPs at 9 selected electrodes for the final word of the first clause (dashed line) and the pre-final word of the second clause (solid line) in neutral sentences (NC) at fast presentation rate (*Petter stänger alltid fönstret så han fryser mindre när ...* “Petter closes always the-window so he freezes less when ...”, target words are underlined). A 200 ms interval preceding sentence-onset was used as the baseline. No effect of Word position was obtained.

The results obtained for *inte* ‘not’ in the postverbal position show a more or less reversed pattern, even though the differences between the presentation rates were not as pronounced as in the case of preverbal *inte* ‘not’. Statistical analysis indicated a more negative response to *inte* ‘not’ relative to the control word at fast presentation rate, suggesting that readers might not have expected main clause word order to the same extent in this condition. The observed enhanced negativity between 175 and 300 ms is smaller than the one seen for preverbal *inte* ‘not’ at slow rate, and it also has a more limited right-posterior distribution. No late positivity was found in this condition. The stronger effects of the negator at slow rate are in accordance with the ‘boundary deletion hypothesis’ (Pauker, Itzhak, Baum, & Steinhauer, 2011): mentally deleting a previously assumed prosodic boundary incurs greater processing costs than inserting an initially missing boundary in both reading (Steinhauer & Friederici, 2001) and listening (Pauker et al., 2011). At slow speed, changing the main clause analysis into a subordinate one would involve the deletion of the preceding prosodic boundary separating the first two clauses. At fast speed, the first two clauses are assumed to initially constitute a single prosodic phrase. In this case, when word order cues main clause structure in the *så*-clause, the revision of the initial syntactic analysis would not require the removal of extra boundaries, explaining the weaker effects at this presentation rate.

6. Conclusions

The findings of the study are consistent with the prediction that embedded clauses would receive different syntactic interpretation depending on the speed with which the sentences are read. At a slow presentation rate where the end of the first clause was reached at 2.7 s, the sentence adverb *inte* ‘not’ indicating subordinate structure for the embedded clause elicited an enhanced negativity. The effect was interpreted as reflecting the detection of an unexpected word order, suggesting that readers were more prepared for an embedded main clause structure after 2.7 s. A positive shift found for the clause-

final word at 2.7 s was tentatively related to the closing of an implicit prosodic phrase, thus indicating that the embedded clause constituted a separate prosodic unit at slow presentation rate, explaining readers' preference for the main clause analysis. The correlation found between individual working memory span and the positivity effect at the prosodic boundary is indicative of the role of time-based working memory constraints limiting the length of prosodic phrases, and, in turn, influencing the syntactic analysis of the investigated embedded clauses. An implication of the findings is that slower readers might interpret the syntactic status of the same clause differently than fast readers. Further research is necessary to identify the precise relationship between reading rate, formal cues to syntactic structure and time-driven implicit prosodic phrasing.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.jneuroling.2015.03.002>.

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