Manipulating syntax without taxing working memory:
MEG correlates of syntactic dependencies in a Verb-Second language

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ABSTRACT

The neural basis of syntax is notoriously difficult to study without working memory and lexico-semantic confounds. To tackle these challenges, we presented dependencies in minimal Danish two-word sentences using Rapid Parallel Visual Presentation (RPVP), which eliminated the temporal delay between a filler and gap. Our stimuli involved dependencies high and low in the tree as a function of manipulating syntactic frame (declarative, yes/no question) and verb argument structure (unergative, unaccusative, alternating unaccusative). Neural magnetoencephalography signals were increased and behaviour facilitated for sentences compared to list controls, replicating the Sentence Superiority Effect (SSE) of prior RPVP studies. Our left-lateral neural SSE at 231–407ms co-occurred with a right-lateral fronto-medial argument structure effect, while syntactic frame affected neural signals at 500–723ms. Thus hierarchically lower dependencies elicited faster neurophysiological correlates, raising the possibility that RPVP may offer a unique window into the brain's detection of syntax when removing temporally extended parsing decisions.

Keywords: Neural bases of syntax; Magnetoencephalography; Rapid Parallel Visual Presentation; Sentence Superiority Effect.

INTRODUCTION

A core assumption of linguistic theories is that language processing is a tandem operation between syntax—the building and parsing of hierarchical structures—and the lexicon. Although we have learned a great deal about the neural bases of lexical access, many more challenges arise when we extend the scope of inquiry beyond that of individual lexical items. Despite nearly three decades of neuroimaging studies, beginning with the by-now-classic study by Stromswold and colleagues (1996), the *when* and *where* of syntax in the brain remain contested. A myriad of functional hypotheses has arisen from hemodynamic studies, ranging from hyperlocalization of syntactic processing in a subpart of the left inferior frontal gyrus (LIFG; Zaccarella & Friederici, 2015) to it relying on an extensive cortical "language network" (Blank et al., 2016; Fedorenko et al., 2020).

As regards the temporal dimension, one of the core findings from electrophysiological techniques such as electroencephalography (EEG) is the so-called P600 effect, which is often believed to reflect syntactic processing at around 600ms post stimulus onset. Interpretations of the component include syntactic reanalysis in garden-path sentences (Friederici, 2002; Osterhout & Holcomb, 1992) and it being a general index of syntactic integration difficulty (Kaan et al., 2000) qualified by dependency length (Phillips et al., 2005) as well as subprocesses of prediction, retrieval, and structure building (Gouvea et al., 2010). Notably, P600 effects have also been observed in response to semantic violations such as semantic verb-argument discrepancies (Kim & Osterhout, 2005; Kuperberg et al., 2003). One account unifying the syntactic and semantic P600 effects argues that the component reflects the continued combinatorial process of assigning structure to a sentence based on both morphosyntactic and semantic-thematic constraints (Kuperberg, 2007). Studies using magnetoencephalography (MEG), with its millisecond temporal resolution and reasonable spatial resolution, have corroborated the findings of both EEG and hemodynamic

studies, e.g., in identifying syntactic P600-like effects often localizing in bilateral temporal regions (Kielar et al., 2015; Service et al., 2007) and in implicating the LIFG in the processing of long-distance dependencies with latencies ranging from ~200ms to 800–1000ms (Leiken & Pylkkänen, 2014; Leiken et al., 2015). Outside the realm of violation paradigms and long-distance dependencies, more recent MEG studies find an early activity increase in the left posterior temporal lobe (LPTL) when contrasting semantically similar expressions of differing syntactic complexity (Flick & Pylkkänen, 2020; Matar et al., 2021). These findings are broadly compatible with a recent model proposing the LPTL as a central locus of syntax especially in comprehension (Matchin & Hickok, 2020; Matchin & Wood, 2020).

Despite the considerable methodological variability in the extant literature, the vast majority of studies have faced the same two fundamental challenges. First, manipulations of syntactic dependencies are often unintentionally entangled with the differential working memory demands imposed by serially unfolding language, a confound inherent of both natural speech and the popular stimulus delivery technique Rapid Serial Visual Presentation (RSVP) delivering words one-by-one. Traditionally, different degrees of syntactic complexity are brought about by contrasting sentences like *What$_i$ did the woman win t$_i$?* and *The woman won the marathon*, the former of which is hypothesised to be more syntactically complex given the need to integrate the displaced *wh*-word in its trace position rather than where it surfaces. Displaced elements therefore need to be held in mind until integration is possible, which increases the load on working memory as compared to sentences without displaced elements. As a result, the extent to which heightened activation to structures with syntactic dependencies is due to syntactic dependencies has been questioned and, at least by some research, challenged. For example, one line of work has suggested that increased activation in the LIFG to syntactically complex sentences reflects articulatory rehearsal

(Baddeley et al., 1975), which facilitates the holding in mind of displaced elements (Fiebach et al., 2005; Rogalsky et al., 2008; Rogalsky & Hickok, 2011). According to this hypothesis, the traditional locus of syntax may instead be a working memory hub.

The other challenge characteristic of much previous research, although the seminal study by Stromswold and colleagues is a notable exception, is that manipulations of syntax often entail varying the lexical material between the simple and complex cases (cf. again *The woman won the marathon* vs. *What$_i$ did the woman win t$_i$?).* This is true for studies looking at elements displaced over short and long distances (Gouvea et al., 2010; Leiken et al., 2015; Phillips et al., 2005) as well as those looking at two-word composition with varying degrees of morphological complexity (Matar et al., 2021). While the simple and complex conditions are (often) minimally contrastive, any variation in the lexical material necessarily presents a potential confound. In contrast, a language like German with relatively free word order makes it possible to compare different sentential configurations of the same lexical items, a phenomenon known as scrambling. EEG studies on scrambling tend to find a "scrambling negativity" when processing the non-canonical word order (Bornkessel et al., 2002, 2003; Schlesewsky et al., 2003). Despite the apparent allure of such word order freedom, scrambled sentences are licensed only within certain information structures (Lenerz, 1977), and the constructions therefore cannot be said to be entirely interchangeable at a discourse-level. Yet another approach to controlling lexico-semantics while varying syntactic complexity has been to manipulate the presence of hierarchical structures by comparing equisized word sequences consisting of individual words, phrases, or sentences (Matchin et al., 2017; Pallier et al., 2011). While these studies keep the lexical material constant across the entire stimulus set, non-sentences are created from the random permutation of sentence fragments from the sentence stimuli, resulting in no one-to-one correspondence in lexical items between individual sentence

and non-sentence stimuli. The stimuli-internal semantics, brought about through the unique combination of lexical items, thus remain uncontrolled.

In this study, a novel methodological combination allows us to address both challenges in an examination of the neural indices of syntax. More specifically, we take advantage of the syntactic properties of Danish to vary the number and type of syntactic dependencies in two-word sentences, each of which are briefly flashed in their entirety followed by a simple matching task during MEG recordings. We vary syntactic frame by manipulating the interrogative force of declarative sentences like *pigen festede* ("the girl partied"; Subject-Verb), turning them into yes/no questions like *festede pigen* ("did the girl party"; Verb-Subject) through a mere word order swap. Notably, the lexico-semantics therefore stay the same across declarative sentences and yes/no questions, even if different discourse-level interpretations are an inherent confound of this specific manipulation like in scrambling studies. As an additional syntactic manipulation, we include verbs that are hypothesised to trigger argument-movement (unaccusative and alternating unaccusative verbs; Perlmutter, 1978) and ones that do not (unergative verbs). The inclusion of two syntactic manipulations allows us to compare any observed effects to each other, with any similarities between them suggesting that they reflect a common underlying operation responsible for resolving syntactic dependencies. We used Rapid Parallel Visual Presentation (RPVP; Snell & Grainger, 2017) as our stimulus delivery technique, which imposes no order processing constraints and therefore makes it possible for the language system to process the input in parallel. Evidence for this comes from the so-called Sentence Superiority Effect (Massol et al., 2021; Pegado et al., 2021; Snell & Grainger, 2017; Wen et al., 2019, 2021a, 2021b), which refers to the faster and more accurate recognition of structured vis-à-vis unstructured representations, in this study elicited by comparing sentences to verb lists. These verb lists paired the intransitive verbs from the sentences

with transitive verbs in both word orders (Transitive-Intransitive and Intransitive-Transitive) to emulate the syntactic manipulations of the sentences to the extent possible while still being devoid of hierarchical structure. Our task was a simple matching task in which half of the trials repeated the target stimulus as the task stimulus and half did not. Crucially, neither processing the stimulus nor doing the task required displaced elements to be held in mind until they could be integrated into the sentence, thus providing minimal, if any, load to working memory.

Any differential processing of the stimuli would provide strong evidence that syntactic structure building is an inherent trait of the language system, even when encountering minimal stimuli that on the surface do not require elaborate structures in order to be interpreted. Here, we discuss the results against the backdrop of generative grammar (Chomsky, 1981, i.a.), but they may equally well be accounted for using other theoretical orientations. The following sections outline assumptions from generative grammar and prior findings from cognitive neuroscience that form the basis of the present investigation.

Manipulating syntactic frame: An overlooked advantage of V2 languages

Unlike their English counterparts *the girl partied* and *did the girl party*, the corresponding Danish declarative sentence *pigen festede* and yes/no question *festede pigen* contain the exact same lexical material. This is a general property of most Germanic languages, stemming from their status as Verb-Second (V2) languages. V2 languages are special in that the finite verb is generally the second unit—a so-called constituent—in a clause (originally proposed by den Besten (1983); see Box 1 for Danish examples). While this is also often the case in an SVO language like English, V2 languages differ in that there are few requirements to the first clause constituent, making it possible for various non-subject constituents to occupy this position. Generative grammar accounts for the

different word orders by assuming slightly different hierarchical structures for V2 and non-V2 languages. Figure 1a-b exemplifies this for corresponding English and Danish declarative sentences. While both the English sentence *the girl partied* and the Danish sentence *pigen festede* involve movement of the subject and the verb from their base-generated positions, the eventual landing sites are higher in Danish than in English. It is precisely the different landing sites of the verbs that allow non-subject constituents to appear before the verb in Danish but not in English. Crucially, the verb and an eligible first-position constitution *must* move to these higher landing sites in V2 languages, even when this additional operation yields the same word order-configuration found prior to movement as is the case in Figure 1b.

(Box 1 around here)

Contrary to their declarative counterparts, Danish yes/no questions like *festede pigen* appear to have V1 order rather than V2 order. Such apparent V1 order (also found in imperatives and other exceptional constructions), however, is typically analysed as being covertly V2. This is achieved by merging a covert question operator—a functional element without phonological content—above the verb, thus forcing the subject to stay below it (Christensen, 2008; Holmberg, 2010, 2015; Vikner, 1995; see also Katz & Postal (1964) for non-V2 accounts of covert question operators). Figure 1b-c provides a comparison of the hierarchical structures for Danish declarative sentences and yes/no questions. Note that although the overall structures of the tree diagrams are comparable, one has more merged elements (yes/no questions) while the other has more syntactic dependencies in the form of displaced elements (declarative sentences). Differences in neural

activation for the two syntactic frames may thus indicate that building one structure is more costly than building the other.

(Figure 1 around here)

Despite offering the possibility to compare different syntactic structures while keeping the lexical material constant, experimental studies taking advantage of such properties of V2 languages remain scarce (but see Den Ouden et al. (2008) for a noteworthy exception). The only other neuroimaging study indirectly taking advantage of the syntactic frame manipulation detailed above (Christensen, 2008) does not report results from comparing these particular conditions.

Manipulating verb argument structure: The Unaccusativity Hypothesis

Although simple Subject-Verb sentences like *the girl partied* and *the girl awoke*, prima facie, seem structurally similar, the arguments of the verbs have different thematic roles. The argument of *partied* is an agent (the "doer" of the event) and the argument of *awoke* a theme or patient (the entity affected by the event). These different thematic relations are believed to stem from different underlying argument structures (Burzio, 1986; Levin & Hovav, 1995; Perlmutter, 1978, i.a.). Whereas the argument of *partied* is a canonical subject, the argument of *awoke* has been hypothesised to originate in the object position before advancing to the subject position. As such, the syntactic derivation of sentences with *awoke*-verbs involves a syntactic dependency not found in sentences with *partied*-verbs. In linguistic theory, this is known as the Unaccusativity Hypothesis and the two types of intransitive verbs as unergative verbs (*partied*-verbs) and unaccusative verbs (*awoke*-verbs). The structural difference between unergative and unaccusative verbs is believed to

explain various linguistic phenomena surrounding resultative constructions (Simpson, 1983), impersonal passivization (Abraham, 1986), and auxiliary selection in a number of Romance and Germanic languages (Haider & Rindler-Schjerve, 1987; Rosen, 1984; Zaenen, 1988). Figure 2 schematises the different argument structures of unergative and unaccusative verbs. So-called alternating unaccusative verbs like *dried*, a subdivision of unaccusative verbs that may optionally be transitive, are also illustrated here.

(Figure 2 around here)

The Unaccusativity Hypothesis has been extensively researched from a theoretical perspective and has also received experimental support from many methodologies, e.g., behavioural studies with neurotypical and/or aphasic participants (Friedmann et al., 2008; Koring et al., 2012; Koring & Van De Koot, 2018; J. Lee & Thompson, 2011; M. Lee & Thompson, 2004; McAllister et al., 2009; Stavrakaki et al., 2011; but see Huang & Snedeker (2020) for a study finding no difference between unergative and unaccusative verbs), fMRI (Agnew et al., 2014; Meltzer-Asscher et al., 2013, 2015; Shetreet et al., 2009; Shetreet & Friedmann, 2012; but see Wang et al. (2021) for a lack of contrast between unergative and unaccusative verbs), and EEG (Martinez de la Hidalga et al., 2019; Zawiszewski et al., 2022). Generally, unaccusative verbs are found to incur a processing cost compared to unergative verbs as evidenced in higher reaction times, higher error rates, increased neural activation, and a general avoidance of constructions with unaccusative verbs. The neural substrates identified as responsible for such asymmetrical processing vary somewhat from study to study. For example, the unaccusative-unergative contrast has been found to implicate as disparate regions as the LIFG (Meltzer-Asscher et al., 2015; Shetreet et al., 2009;

Shetreet & Friedmann, 2012), the left superior frontal gyrus (Shetreet et al., 2009), the left middle temporal gyrus (Shetreet et al., 2009; Shetreet & Friedmann, 2012) as well as bilateral superior temporal gyri (Agnew et al., 2014). Similarly, contrasting alternating unaccusative verbs with non-alternating intransitive verbs has sometimes resulted in increased activation in bilateral posterior perisylvian regions as well as bilateral middle and superior frontal gyri (Meltzer-Asscher et al., 2013) and at other times in no differential activation (Meltzer-Asscher et al., 2015).

The current study

Aim 1: The neural indices of syntactic dependencies in a working memory-free paradigm

The main purpose of this study is to investigate how syntactic dependencies—here instantiated through the manipulation of syntactic frame and verb argument structure—are processed neurally when working memory-related costs are eliminated. If the brain has a unified hub responsible for computing syntactic dependencies, regardless of the type, the same brain region(s) should be responsive to the manipulation of both syntactic frame and of verb argument structure. As such, neural activity may be modulated as a function of the number of movement operations (see Figure 3 for a schematization). Alternatively, the brain may distinguish between different types of syntactic dependencies, resulting in the two manipulations engaging distinct brain regions. Since this is the first investigation of the neural correlates of syntactic dependencies when freed from seriality constraints and dissimilar working memory costs, the effects may be quite different from those identified in prior literature, and we therefore remain agnostic to their localization in time and space.

(Figure 3 around here)

Aim 2: Parallel presentation of full sentences—the Sentence Superiority Effect in the brain

The use of RPVP as stimulus delivery technique additionally allowed us to investigate—as a secondary research question—the neural bases of the Sentence Superiority Effect that have been observed in prior RPVP literature. The Sentence Superiority Effect illustrates the impressive speed at which the language system operates when presented with stimuli in their entirety for just a few hundred milliseconds. Using EEG, Wen et al. (2019, 2021) have further addressed the neural signature of the Sentence Superiority Effect over time, finding it to manifest as an N400-type effect. Specifically, they observed reduced amplitudes for grammatical sentences compared to scrambled ones from 274-410ms, which they interpreted as a facilitation effect guided by the interactive processing of word identities and a rapidly generated syntactic representation. While we anticipate an approximate replication of the timing of the effect, we expect the Sentence Superiority Effect to manifest as increased neural activation to sentences compared to lists in line with previous MEG research, beginning with Bemis & Pylkkänen (2011), comparing structured and unstructured representations in RSVP.

METHODS

Participants

Twenty-nine Danish-speaking individuals were recruited to participate in the study (14 females, 15 males; mean age = 29.48, SD = 8.49) through word-of-mouth and advertising on social media. Since the study was conducted in the New York City area, participants comprised a diverse group including tourists and long-term expats, and information about their language use and proficiency levels was therefore collected using a modified version of the language background questionnaire LEAP-Q (Language Experience and Proficiency Questionnaire; Marian et al., 2007). All

participants claimed Danish as their native language (mean age of acquisition = 0.07, SD = 0.37), even if some participants had grown up in households where a language other than Danish was also spoken (n = 7). On a 1–10 rating scale, all participants assessed their speaking, listening, and reading skills in Danish to be at ceiling (speaking: mean rating = 9.90, SD = 0.41; listening: mean rating = 9.97, SD = 0.19; reading: mean rating = 9.90, SD = 0.31). All participants were neurologically intact with normal or corrected-to-normal vision. Participants provided their informed written consent and were paid $30 for their participation. The study was approved by the Institutional Review Board (IRB) ethics committee of New York University (approval number 2016-91).

Stimuli

The study employs a 2 × 2 × 3 factorial design varying composition (COMP), syntactic frame (SYN), and verb argument structure (ARG). First, a battery of diagnostics was employed to identify Danish verbs that could be classified as unergative, unaccusative, or alternating unaccusative. The diagnostics were: (i) auxiliary selection in the perfect, (ii) ability to occur with a reflexive pronoun in resultative constructions, (iii) ability to occur in impersonal passive constructions, (iv) ability to form nominal modifiers from the past participle, (v) ability to occur with direct objects, and (vi) ability to undergo passivization. Diagnostics (i-iv) separated unergative verbs from unaccusative and alternating unaccusative verbs (see Levin & Hovav (1995) a review of these diagnostics) whereas (v-vi) were tests of transitivity, primarily used to distinguish unaccusative verbs (intransitive) from alternating unaccusative verbs (optionally transitive). Since different diagnostics may group verbs into slightly different categories, we chose a conservative approach requiring verbs to align with the requirements of each diagnostic for a given verb category. Verb classification was based on the judgments of the first author, who is a native speaker of Danish, and cross-checked

with dictionary definitions (Den Danske Ordbog; DSL, 2021) and corpus frequencies from a Danish corpus (KorpusDK; Asmussen, 2012, 2015). For example, (i) the auxiliary selection-diagnostic refers to the fact that Danish has a split auxiliary system, that is, some verbs take the auxiliary *være* ("to be") and others the auxiliary *have* ("to have") in the perfect (Bentley & Eythórsson, 2004; Bjerre & Bjerre, 2007; Larsson, 2014). The choice of auxiliary is tightly correlated with the unaccusativity of the verb, with unaccusative verbs employing the auxiliary *være* and unergative and transitive verbs the auxiliary *have*. Here, we determined the appropriate auxiliary for each verb by first consulting the dictionary definitions, which specify whether a verb takes *være, have,* or either auxiliary in the perfect. This information was then ratified using corpus searches to compare the ratios of *være* and *have* used with each verb. In cases of doubt, for example if the corpus searches did not yield many occurrences, decisions were made by the first author. Similar processes were repeated for the other diagnostics.

A total of twenty-seven intransitive verbs were chosen as critical verbs, resulting in nine verbs for each of the three categories of ARG. Efforts were made to reflect a wide range of meanings for each category of verbs. Independent t-tests largely failed to show statistically significant differences between the three verb types for the following lexical characteristics: number of letters, syllables, morphemes, and phonemes as well as word frequencies (see Table 1). However, the unergative–unaccusative contrast did reveal a significant difference in the number of morphemes ($p = 0.0353$) and the unaccusative–alternating unaccusative contrast a difference in the number of letters ($p = 0.0128$) and morphemes ($p = 0.0353$). While full control of lexical characteristics for the three verb types had been desirable, strict control with the argument structure of the verbs was deemed more important for the purpose of the present study. Then, each of the twenty-seven intransitive verbs was paired with nine definite nouns. The nouns were 5–7 letters long with generic

person reference, e.g., the Danish equivalents of *the girl* or *the man.* All verbs were in the past tense due to the homonymous nature between many Danish nouns and present tense verbs, and past tense verbs thus enforced compositional rather than list interpretations of the sentences. All intransitive verbs and nouns were paired in two ways corresponding to the two levels of SYN: Subject-Verb (declarative sentences) and Verb-Subject (yes/no questions). Crucially, the Verb-Subject word order unequivocally produces a yes/no question and, in line with standard practices regarding the use of punctuation in experimental research, we chose to not include a question mark for the yes/no questions. The transition probability between the two word orders for the verbs in question, as calculated using KorpusDK, did not differ significantly ($p = 0.2108$). While this metric is somewhat conflated since the Verb-Subject order is also found with preposed non-subject constituents, it suffices to dispel structural frequency-interpretations of potential effects. In sum, each SYN-ARG combination resulted in 81 sentences, producing a total of 486 sentences.

(Table 1 around here)

Finally, a control condition with two-word lists was created by replacing the nouns in each of the 486 sentences with nine transitive past tense verbs. The transitive verbs matched the nouns in length (5–7 letters) and passed all diagnostics outlined in Box 2. Verb lists were preferable to noun lists as they effectively mitigated any unintended composition effects arising from two-word noun lists (e.g., due to noun-noun compounding or the aforementioned homonymous nature between many Danish nouns and present tense verbs). The complete stimulus set thus had 972 trials. Each stimulus subtended a horizontal visual angle between 4.75° and 6.58° (mean ± SD visual angle: 5.44° ± 0.48°). See Figure 4a for the complete factorial design.

(Box 2 around here)

(Figure 4 around here)

Task rationale and trial structure

While the majority of studies using RPVP have employed grammaticality judgments or post-cued partial report, we opted for a straightforward matching task in which participants identified whether target and task stimuli were the same (a match trial) or different (a mismatch trial) (see Pegado et al., (2021) for a similar task). Main motivations for the task were its speed and the absence of any explicit judgments on the stimuli. Since the task can be performed purely perceptually, any effects of our structural manipulations would be reflective of truly automatic processing. The choice of a different task is also corroborated by Wen and colleagues' (2019, 2021) findings that an N400-like Sentence Superiority Effect arises using RPVP independent of the task employed. In our study, only one of the two words differed between the target and task stimuli, with swapped words always being of the same length and belonging to the same category (noun, transitive verb, intransitive verb). The identity and position of the swapped words were randomised across the 972 trials. Note that only responses to the first sentence of a trial (the target stimulus) and not the second sentence (the task stimulus) were analysed.

The structure of each trial was as follows (see Figure 4b). First, a fixation cross was displayed (200ms) followed by a blank screen (200ms). Next, the target stimulus was briefly flashed (300ms) and then followed by another blank screen (500ms). Lastly, the task stimulus was displayed until the participant, via button-press, indicated the trial as being either a match or a mismatch trial. Behavioural reaction times were measured from the presentation of the task stimulus.

The intertrial stimulus interval was 600–750ms, jittered in increments of 50ms. The 972 trials were randomly divided into nine blocks of 108 trials each and presented centrally on a screen in Courier New-font using PsychoPy 2022.2.4 (Peirce et al., 2019).

Procedure

The experiment took place at the NYU/KIT MEG LAB at New York University, New York. Upon arrival to the lab, participants gave informed consent and filled out modified versions of a handedness questionnaire (Oldfield, 1971) and the LEAP-Q questionnaire on paper. Next, participants' head shapes were 3D digitised using a Polhemus FastSCAN laser scanner (Polhemus, VT, USA) to enable coregistration of the MEG data with the FreeSurfer fsaverage brain (Fischl, 2012) during analysis. Five future marker coil placements and the position of three fiducial landmarks (nasion, left tragus, right tragus) were included in the digitizations. The head shape-scans were followed by a brief instruction period and a practice session of 12 trials mirroring the actual experiment in structure and task but with different stimuli. Participants were then guided into the dimly lit magnetically shielded room hosting the MEG machine where marker coils were placed on the digitised points before the participants completed the experiment in supine position. Each experimental session took ~2 hours.

MEG data acquisition and preprocessing

Continuous MEG data were recorded using a whole-head, 157-channel axial gradiometer system (Kanazawa Institute of Technology, Kanazawa, Japan) at a sampling rate of 1000Hz with online high- and low-pass filters of respectively 1Hz and 200Hz. Participants' head positions relative to the MEG sensors were recorded using marker coils before and after the experiment.

The MEG data were first noise-reduced based on data collected from reference channels using the Continuously Adjusted Least-Squares Method (Adachi et al., 2001) in the MEG160 software (Yokogawa Electrical Corporation and Eagle Technology Corporation, Japan). All other preprocessing steps were conducted using the MNE-Python v0.23.4 (Gramfort et al., 2014) and Eelbrain v0.31.8 (Brodbeck et al., 2019) packages in the Python computing environment. First, an offline 1–40 Hz bandpass filter was applied, and flatlined or clearly malfunctioning channels (averaging 2.4 channels per participant) were removed and interpolated using the remaining sensors. Epochs were then extracted from 100ms before to 800ms after the onset of the target stimulus; as such, only processing of the target stimulus—not the task stimulus—was included in an epoch. Afterwards, Independent Component Analysis (ICA) was performed to remove artifacts such as eye blinks, saccades, heartbeats, and well-characterised external noise sources. Individual epochs were rejected if they contained amplitudes exceeding 3000 fT or, upon visual inspection, contained sudden increases in the magnitude of the signal (as caused by, e.g., muscular movements), resulting in the removal of 1.88% of epochs. Finally, the number of epochs was balanced across conditions, leaving on average ~96.13% of epochs for each participant, and baseline corrected using the 100ms before the onset of the target stimulus.

Dynamical Statistical Parameter Mapping (dSPM; Dale et al., 2000) was used to create cortically constrained estimates of source-level activity for the analyses. During coregistration, the digitised head shape and fiducial landmarks of each participant were scaled and mapped to the Freesurfer fsaverage brain in the creation of cortical surfaces. From these, two source spaces of 2,562 sources (one per hemisphere) were generated and, using the Boundary Element Model (BEM) method, a forward solution computed. A noise covariance matrix was then calculated using the first 100ms of the epoch, which, in tandem with the forward solution, formed the basis for

computing inverse solutions with free orientation. Lastly, the noise-normalised minimum norm estimates were converted to dSPMs, enabling spatiotemporal visualizations of activity.

Statistical analyses

Behavioural data

In order to test for behavioural correlates of the Sentence Superiority Effect and our syntactic manipulations, we first cleaned the data of responses more than 3 SDs from overall participant or item means. For response times, we then fitted a linear mixed-effects regression model to log-transformed reaction time data for the correct responses with COMP, SYN, ARG, and task type (TASK; match/mismatch trial) as fixed effects alongside all possible interaction terms. TASK was included as a fixed effect in the behavioural analyses due to the expectation that match and mismatch trials would asymmetrically recruit cognitive resources; match trials involved priming between target and task stimulus while mismatch trials did not. In terms of random effects, the maximal structure that converged included by-participant and by-item varying intercepts. Accuracy data were analysed using a generalised linear mixed-effects logistic regression model (incorrect responses included) with the same structure of fixed effects but with just by-participant intercepts. All *p* values were generated via likelihood ratio tests, and pairwise comparisons were corrected using a Tukey adjustment. The analyses were conducted using the *lme4* (Bates et al., 2015) and *afex* (Singmann et al., 2023) packages in R (v4.3.1) and RStudio (v2023.06).

MEG data

The analyses of the MEG data were largely exploratory given the use of RPVP, a stimulus delivery technique novel to MEG research, which allowed us to investigate the neural indices of the

Sentence Superiority Effect and of syntactic dependencies freed from differential working memory costs. As such, we performed nonparametric spatiotemporal cluster tests (Maris & Oostenveld, 2007) in liberal search areas to maximally capture the effects of our manipulations.

First, we fitted a 2 × 2 × 3 repeated measures ANOVA with factors COMP (sentence, list), SYN (declarative sentence, yes/no question), and ARG (unergative verb, unaccusative verb, alternating unaccusative verb) to the data in bilateral full-hemisphere searches across the entire epoch (0–800ms) to assess instantiations of a Sentence Superiority Effect. Next, to probe for effects of our syntactic manipulations, we dropped all list stimuli and performed 2 × 3 repeated measures ANOVAs with factors SYN and ARG on the sentence stimuli only. We did so in bilateral full-hemisphere searches across the entire epoch as well as in bilateral lobe-by-lobe searches in early (100–500ms) and late (500–800ms) time windows. While effects of our syntactic manipulations could also have been tested using the full factorial design—in so doing looking for effects of SYN or ARG modulated by COMP—we chose to separate sentences from lists based on the undertheorised nature of the computations underlying two-verb list processing. Furthermore, the more subtle contrasts in the levels of SYN and ARG compared to COMP motivated the use of narrower spatiotemporal search areas. In terms of temporal delineation, we opted for time windows that could capture common EEG components like the N400 and the P600 respectively. As to spatial delineation, we chose the more generous search areas of lobes over narrower regions identified in prior literature on syntactic processing, e.g., the LIFG or the LPTL, since our working memory-free paradigm using parallel stimulus presentation might engage brain regions different from those recruited during serial stimulus presentation.

All spatiotemporal permutation clustering tests were performed in Eelbrain v0.37.6 (Brodbeck et al., 2022) using a standard procedure. An uncorrected repeated-measures ANOVA

was fitted to each spatiotemporal dimension (region of interest/time window) to calculate *F* values for source-time point combinations. Clusters were computed from adjacent spatial and temporal values when these met the cluster-forming threshold of $p < 0.05$. Then, cluster *F* values were summed if the cluster consisted of a minimum of 20 vertices and 20 contiguous time points, yielding a cluster-level statistic. We determined significance using a cluster-based (Monte Carlo) permutation test, generating a null distribution of the test statistic for each spatiotemporal dimension by randomly shuffling condition labels for each participant 10,000 times. The observed clusters were then compared to the null distribution and assigned corrected *p* values that reflected the proportion of permuted clusters with sizes larger than the actually observed cluster. In the lobe-by-lobe analyses, the resulting *p* values were corrected for multiple comparisons across ipsilateral lobes by controlling the false discovery rate at the critical value of 0.05 (Benjamini & Hochberg, 1995). Given the uncorrected nature of the clusters initially chosen for analyses, the borders of the reported clusters should be interpreted as approximate, thus making it impossible to make exact claims about latency or duration of any effects (Sassenhagen & Draschkow, 2019).

RESULTS

Behavioural results

As shown in Figures 5 and 6, we found clear behavioural instances of the Sentence Superiority Effect for response times and to some extent for accuracies. This asymmetry between response times and accuracy is expected given the short stimuli and the simple nature of the task, which also resulted in very high overall task accuracies (mean ± SD: 96.42 ± 2.61%) and low response times on correct trials (679.56 ± 228.63ms). As for our syntactic dependency manipulations, the

only significant difference of interest was a difference in the processing of sentences with unaccusative verbs in match trials. See Table 2 for all likelihood ratio test results.

(Table 2 around here)

(Figure 5 around here)

Behavioural instances of the Sentence Superiority Effect for response times and accuracies

The significant effects of COMP and TASK patterned as expected. Responses were faster and more accurate on sentences (664.33 ± 208.40ms; 96.89 ± 2.33%) than lists (695.01 ± 246.51ms; 95.95 ± 2.99%), providing an instance of the Sentence Superiority Effect. Similarly, responses to match trials were faster and more accurate (667.03 ± 238.30ms; 96.65 ± 3.12%) than to mismatch trials (692.13 ± 217.80ms; 96.16 ± 2.80%). Furthermore, as suggested by the significant interaction effect between COMP and TASK for response times, the extent to which one effect modulated the other varied. As such, although pairwise comparisons revealed significant Sentence Superiority Effects for both match and mismatch trials in isolation (both $p < 0.001$), it was more pronounced for match trials (average difference in response time between sentences and lists: 36.41ms) than mismatch trials (25.16ms). Similarly, while sentences and lists each had significantly faster response times for match trials compared to mismatch trials (both $p < 0.001$), pairwise comparisons found the impact of TASK to be greater for sentences (average difference in response time between match and mismatch trials: 30.83ms) than for lists (19.57ms). Figure 5 illustrates—across the entire factorial design—the significant effect of COMP on response times for (a) all trials, (b) match trials, and (c) mismatch trials as well as the significant three-way interaction between COMP, SYN, and ARG on

accuracies for (d) all trials, (e) match trials, and (f) mismatch trials. Main effects of COMP for response times and accuracies are depicted in the right panel of Figure 6.

A syntactic frame effect for sentences with unaccusative verbs in match trials

Behavioural support for syntactic dependency effects required SYN or ARG to be modulated by COMP since the distinction between sentences and lists is otherwise conflated. The significant main effects of SYN and ARG in the response time data are thus not of interest for the present purposes, not least because post-hoc decomposition of the effects revealed them to be driven by lists rather than sentences. The interaction effect between SYN and TASK in the response time data is similarly confounded by COMP and therefore also not of interest. Moving next to the accuracy data, the only noteworthy findings from the pairwise comparisons of the three-way interaction effect of COMP, SYN, and ARG are condition-specific Sentence Superiority Effects (declarative sentences with unaccusative verbs: $p = 0.003$; yes/no questions with alternating unaccusative verbs: $p = 0.0023$). Adding TASK to examine the four-way interaction effect again revealed Sentence Superiority Effects for specific SYN-ARG combinations (declarative sentences with unaccusative verbs in match trials: $p = 0.002$; yes/no questions with unergative verbs in match trials: $p = 0.0459$; yes/no questions with alternating unaccusative verbs in match trials: $p = 0.0053$). Notably, an effect of SYN was also found for sentences with unaccusative verbs in match trials (declarative sentences were significantly more accurate than yes/no questions: $p = 0.0081$).

To conclusively determine the impact of including COMP in the full models, two models with SYN, ARG, and TASK as fixed effects were fitted to the response time and accuracy data obtained for the sentences only. This reduced the number of significant effects substantially as expected, leaving only a main effect of TASK in both the response time and accuracy data as well as

a three-way interaction between SYN, ARG, and TASK in the accuracy data. All of these patterned as the full models and are therefore not reported here.

MEG results

A fronto-temporal Sentence Superiority Effect in the left hemisphere

To uncover any neural correlates of the Sentence Superiority Effect, we ran a 2 (COMP: sentence, list) × 2 (SYN: declarative sentence, yes/no question) × 3 (ARG: unergative verb, unaccusative verb, alternating unaccusative verb) repeated-measures ANOVA in each hemisphere. The ANOVA revealed a left-lateralised effect of COMP ($p = 0.0171$) in our test window of 0–800ms after onset of the target stimulus. The cluster extended from ~230ms to 405ms and had a broad fronto-temporal distribution, with sentences eliciting more activity than lists (see Figure 6).

Additionally, we found a patchwork-like effect of ARG ($p = 0.0173$) scattered across the left hemisphere from approximately 85–200ms, with unergative verbs eliciting less activity than both unaccusative and alternating unaccusative verbs. Since post-hoc tests revealed it to be driven by list stimuli exclusively, we will not examine it further. We did not observe any clusters in the right hemisphere using this full factorial design.

(Figure 6 around here)

Right-lateralised responses to syntactic dependencies

The second round of analyses was specifically aimed at finding effects of our syntactic dependency manipulations unobscured by the list stimuli, and repeated-measures ANOVAs with factors SYN and ARG were therefore run on the sentence stimuli in isolation. Our exploratory analysis looking

for effects across each hemisphere in the entire epoch did not reveal any left-lateral effects. However, we did detect a significant right-lateral effect of ARG ($p = 0.0399$) from ~260–375ms (Figure 7a). The effect was quite expansive and included multiple fronto-medial areas. Planned t-tests found significantly more activity for unergative verbs relative to unaccusative verbs (284–364ms; $p < 0.0001$) and alternating unaccusative verbs (326–364ms; $p = 0.0178$). There was no significant difference between unaccusative and alternating unaccusative verbs (all $p > 0.16$).

Although our manipulation of ARG was conceptualised as varying the number of syntactic dependencies in a sentence, the three verbs may be partitioned in the same way based on their lexico-semantic characteristics. In other words, it is as likely that sentences with unergative verbs are different from sentences with unaccusative or alternating unaccusative verbs because they differ in the number of syntactic dependencies as it is due to different thematic role assignment. Notably, however, such conflation of syntax and semantics is not found for the list stimuli, which are presumed to be devoid of syntactic structure. To tentatively address whether the observed effect of ARG was syntactic or semantic in nature, we extracted the spatial extent of the cluster and used it to perform a post-hoc spatiotemporal clustering test from 200–400ms post stimulus onset using the full data set (sentences and lists). If the effect was related to verb-level semantics, we would expect to see the main effect of ARG replicated given that all stimuli drew from the same set of intransitive verbs, especially due to the much narrower spatiotemporal search window of the clustering test. We did not see such a replication, which provides support for a syntactic interpretation of the effect. As a final step, we also ran the analysis with only the list stimuli, again finding no replication.

The bilateral lobe-by-lobe searches in early (100–500ms) and late (500–800ms) time windows revealed two effects of SYN that remained significant after correcting for multiple

comparisons. The first cluster (uncorr. p = 0.0208, corr. p = 0.0416) localised in right occipital areas at around 500–555ms, with declarative sentences eliciting more activity than yes/no questions (Figure 7b). Later, at around 640–725ms, a second cluster (uncorr. p = 0.0137, corr. p = 0.0416) with the opposite activation pattern (yes/no questions eliciting more activity than declarative sentences) emerged in the right parietal lobe (Figure 7c). We also found two significant clusters in the left hemisphere—an interaction between SYN and ARG at ~225–320ms in the parietal lobe and a main effect of SYN at ~655–700ms in the frontal lobe—but none of these survived multiple comparisons correction (both $p > 0.12$). None of the SYN effects emerged when we performed a round of post-hoc tests following the same analysis pipeline on the list stimuli only. This suggests that the effects originate in linguistic computations rather than being mere artifacts of swapping the word order.

To complete our analyses of syntactic dependency effects, we performed post-hoc analyses with factors SYN and ARG probing the left fronto-temporal cluster obtained for our Sentence Superiority Effect across the full epoch as well as in the early and late time windows. This did not yield any significant clusters (all $p > 0.14$).

(Figure 7 around here)

DISCUSSION

In this study, we employed a novel combination of Danish stimuli and Rapid Parallel Visual Presentation (RPVP) to explore the neural signatures of syntactic dependency manipulations when freed from the differential working memory costs inherent of serial processing. Specifically, we varied the syntactic frame (SYN; declarative sentences, yes/no questions) and the argument

structure of intransitive verbs (ARG; unergative, unaccusative, alternating unaccusative). The choice of stimulus delivery technique additionally allowed us to explore, for the first time with minimal two-word sentences and lists (COMP; sentences, lists), the behavioural and neural correlates of the so-called Sentence Superiority Effect.

Each of our manipulations (COMP, SYN, ARG) resulted in differential processing neurally and, in the case of COMP and SYN, behaviourally. Below we discuss first the instance of the Sentence Superiority Effect obtained in the present study before turning to possible interpretations of the ARG and SYN results. Common to all our experimental manipulations, however, is that the neural responses we observe are to some extent determined by the way language was delivered. While seriality is an inherent characteristic of spoken language, we find evidence that the language system is highly flexible and can extract vast amounts of information from parallelly presented input. The fact that we observe these differences even for minimal two-word sentences—whether all or only some effects can be ascribed to syntactic dependencies—underscores the automatic processes involved in all language processing, regardless of the complexity of a given stimulus.

A behavioural and neural Sentence Superiority Effect for minimal structures

This study adds to a growing body of work, spearheaded by Snell & Grainger (2017), that investigates a phenomenon where sentences enjoy a processing advantage compared to their unstructured counterparts. We find substantial support for such a Sentence Superiority Effect, notably obtained using shorter stimuli (two-word sentences vs. two-word lists) than those of prior studies. Like previously, we found response times to be shorter and accuracies higher for sentences than for unstructured representations. Neurally, we see a broadly distributed instance of the Sentence Superiority Effect in left fronto-temporal regions at around 230–405ms, with sentences eliciting

more activity than lists. Our MEG results thus mirror those reported by Wen and colleagues in terms of timing in addition to adding information about the localization of said effects. Although the directionality of the MEG data is the opposite of Wen and colleagues' EEG studies—they found reduced activity for sentences relative to their scrambled counterparts—it aligns well with a comprehensive body of MEG research finding increased activity for two-word phrases over two-word lists (see Pylkkänen (2019, 2020) for reviews). Crucially, our behavioural and neural Sentence Superiority Effects are obtained using a simple matching task, which could be performed purely based on perceptual similarity. The fact that we still see a difference between the processing of sentences and lists therefore underscores the language system's preference for structured representations.

As one of the first studies exploring the neural correlates of the Sentence Superiority Effect, we had no specific hypotheses as to where the effect might localise. It seemed plausible, however, that we would see an effect with a widespread distribution given that our contrast—sentences vs. lists—was a gross one with both syntactic and semantic differences. The left fronto-temporal cluster we identified encompasses typical language-processing regions like the LIFG and the left anterior temporal lobe (LATL). As regions frequently implicated in, respectively, syntactic processing and conceptual combination (Bemis & Pylkkänen, 2011), it is not unexpected to see an instance of the Sentence Superiority Effect localizing here. However, other areas like the middle-posterior temporal lobe and inferior parts of the parietal lobe, both of which have been identified as quintessential language regions (e.g., Fedorenko et al., 2010; Fedorenko & Thompson-Schill, 2014), are conspicuous in their absence. One possible explanation for this could be related to the nature of our control condition. We chose a two-verb list condition to avoid unintended composition effects arising from the homonymous nature of many Danish nouns and verbs, but it is possible

that the verb-list contrast as opposed to the frequently used noun-list contrast may have washed out significant differences between sentences and lists. More research using different kinds of contrasts to elicit the Sentence Superiority Effect is needed to clarify this point.

While we find support for the existence of a Sentence Superiority Effect, it also brings to the fore a crucial question: What aspects of sentence processing actually underpin this Sentence Superiority Effect? The different spatial loci of our Sentence Superiority Effect (a left fronto-temporal cluster) and syntactic dependency effects (various right lateral clusters) suggest that they stem from different linguistic computations; if not, we would have expected some degree of overlap between the effects of COMP, SYN, and ARG. Since our syntactic manipulations are exactly that—i.e., manipulations of an existing syntactic structure—it seems likely that the Sentence Superiority Effect reflects the output of more basic sentence-building operations, the manipulation of which happens elsewhere in space and, to some extent, time. Exactly what such basic sentence-building operations involve is a promising avenue for future research to deconstruct.

Rapid assembly of verb argument structure in the right hemisphere

Of our two syntactic dependency manipulations, we first saw effects of manipulating verb argument structure. This refers to the fact that intransitive verbs come in different flavors based on the thematic roles they assign to their arguments, which in turn reflects distinct syntactic structures. While the subject of an unergative verb like *party* originates in the subject position, unaccusative and alternating unaccusative verbs like *awake* and *dry* attract the object-generated argument to the subject position.

In this study, we find support for a neural distinction between unergative verbs on the one hand and unaccusative and alternating unaccusative verbs on the other. This manifested in the

MEG data as a right-lateralised fronto-medial cluster at ~260–375ms, with significantly increased activation for the processing of unergative verbs as compared to the two other verb types. This effect was only found for the sentence stimuli and not the combined data set (sentences and verb lists, both of which were formed from the same set of intransitive verbs), which supports a syntactic rather than verb-level semantic interpretation.

Previous neuroimaging literature has implicated a variety of brain regions in the processing of intransitive verbs, most often involving left perisylvian regions. As such, the right lateral effects observed in this study are somewhat unexpected although not without precedence. For example, Agnew et al. (2014) found significantly differential activation in bilateral superior temporal gyri when comparing unaccusative verbs to unergative verbs embedded in sentences presented auditorily. An even more poignant example is that of Meltzer-Asscher and colleagues (2013), who report bilateral perisylvian and, like in the current study, superior frontal effects for alternating unaccusative verbs compared to unergative verbs presented visually and in isolation. These two studies exemplify the predominant procedures used in neuroimaging studies investigating verb argument structure; either sentences with intransitive verbs are presented auditorily, or intransitive verbs are presented visually in isolation. A one-to-one comparison between our results—obtained from a working memory-free paradigm using parallel visual presentation of sentences—and previous findings is thus not merited.

Interestingly, we saw increased activation to the syntactically simpler sentences with unergative verbs as compared to sentences with unaccusative and alternating unaccusative verbs. This finding is surprising in the light of previous fMRI literature on the topic, which tends to report the reverse pattern. However, it is not unlike that of recent MEG studies investigating structural differences in minimally contrastive expressions, finding increased activity when syntactic

composition is more straightforward (Flick & Pylkkänen, 2020; Matar et al., 2021). It remains an open question exactly how to interpret this effect, but one possibility is that syntactically simpler structures induce converging neural activation to a higher extent than do syntactically complex structures. It is a known artifact of electrophysiological methods like MEG that a loss in signal magnitude may reflect cancellation effects from the concurrent activation of neighboring brain regions (Ahlfors et al., 2010). A hemodynamic method like fMRI, on the other hand, makes it possible to observe signals from individual voxels largely independent from each other, thereby allowing an unobscured picture to emerge. Relegating the directionality of the activation pattern we observe to a methodological difference is at this point speculative but stresses the need for parallel experimental designs across methodologies.

Late, right-lateralised effects of manipulating the syntactic frame

In contrast to the verb argument structure manipulation, effects from manipulating the syntactic frame showed up considerably later. In Danish, declarative sentences and yes/no questions differ exclusively in their word order. This property allowed us to manipulate the syntactic structures of two-word sentences with intransitive verbs like, e.g., the declarative sentence *pigen festede* ("the girl partied") and the yes/no question *festede pigen* ("did the girl party"), while keeping lexical semantics constant. Current accounts from linguistic theory schematise this difference as a structure with fewer syntactic dependencies for yes/no questions than for declarative sentences arising from the V2 properties of Danish.

Interestingly, the brain is able to detect the subtle difference between declarative sentences and yes/no questions, even when the stimuli are presented for a short amount time as done in RPVP. Our MEG data revealed two significant effects of SYN: one localizing in right occipital

areas at around 500–555ms and another localizing in right parietal areas at around 640–725ms. Post-hoc tests on the list stimuli did not replicate the effects, and the effects therefore do not simply reflect the change in word order. We also saw a behavioural interaction effect for sentences with unaccusative verbs in match trials, with declarative sentences being recognised more accurately than their interrogative counterparts. Crucially, the two neural effects differed not only in timing and spatial origin but also in directionality. Whereas the cluster in right occipital areas saw more activity for declarative sentences than for yes/no questions, the opposite pattern was observed for the cluster in right parietal areas. Coupled with the spatiotemporal differences, it seems likely that the two clusters reflect different computations.

Since no other studies have employed this contrast between declarative sentences and yes/no questions, and because our effects localise to regions not typically implicated in language processing, interpretations of the results are at this point conjectural. It is quite possible that one or both of the effects pertains to syntactic restructuring since accounts from theoretical linguistics hypothesise declarative sentences to have more syntactic dependencies than yes/no questions. This could manifest as increased activation to declarative sentences due to increased syntactic complexity, as in the right occipital cluster observed. Alternatively, as argued regarding the verb argument structure effect, it might even result in decreased activation for declarative sentences given a lack of converging neural activity for this syntactically more complex structure, as in the right parietal cluster observed. Our design unfortunately does not allow us to adjudicate between these different interpretations. That being said, yes/no questions and other similar constructions in V2 languages have received somewhat limited attention in theoretical linguistics, and it is therefore also possible that other syntactic structures capture the differences more appropriately.

At least two other hypotheses regarding the origins of the SYN effects ought to be entertained. First, it is possible that we are seeing structural frequency effects if the overall distribution of the two word orders (Subject-Verb and Verb-Subject) is skewed. Given the preponderance of factual knowledge expressed using declarative sentences in linguistic exchanges, assuming such an asymmetric distribution would be warranted had it not been for the possibility to prepose non-subject constituents, like objects or adverbials, in declarative sentences in V2 languages. Since the corpus transition probabilities for the two word orders were controlled, we can rule out a structural frequency interpretation of the results.

The second alternative hypothesis relates to the discourse-level interpretation of the sentences—what do the sentences actually mean? Given the long latency of the syntactic frame effects, it is possible that one or both may reflect such higher-level processing. Again, however, the lack of prior research tracking the temporal evolution of sentential representations from parallelly presented stimuli, coupled with our novel syntactic frame manipulation, makes it difficult to directly compare our findings to existing literature. Nevertheless, a brief mentioning of a recent study by Tulling et al. (2021) is in order. Here, they contrasted factual expressions with modal verbs expressing possibility and necessity embedded in short narratives and presented in RSVP, which produced a significant cluster at ~200–350 after target verb onset in the right inferior parietal sulcus, with increased activity to factual expressions. They ascribed this effect to a procedure of discourse-model updating, that is, a revision of one's mental representation of a situation.

Although the factual verbs–modal verbs manipulation employed by Tulling and colleagues is distinct from our declarative sentence–yes/no question manipulation, both contrasts rely on the otherwise under-researched distinction between realis and irrealis moods. Realis moods express statements of facts whereas irrealis moods express unreality, that is, referencing events that have

not happened (or are not known to have happened). As such, the spatial overlap between Tulling et al.'s findings and our right parietal cluster is remarkable, even though they observed the reverse activation pattern (realis > irrealis) than what we did (realis < irrealis). There are numerous differences between the two studies (the stimuli, the stimulus delivery technique, contextual embedding), and future research might therefore benefit from experimental designs allowing more direct comparisons of different instantiations of the realis–irrealis distinction, perhaps even examining potential interactions by embedding modal verbs in yes/no questions.

Temporal ordering of syntactic manipulations suggests syntactic dependencies low in the syntactic tree being resolved before those higher up

Just like we had little idea as to *where* our syntactic dependency manipulations would manifest when unconstrained by serial presentation constraints, we did not know *when* we might see such effects. Given the factorial design, it was possible that we would see interaction effects between the two syntactic dependency manipulations. That is, differences in activation could have been modulated as a function of SYN and ARG, either cumulatively in the same brain region(s) or concurrently in distinct brain regions. On the other hand, a lack of interaction effects would suggest temporally separable computations associated with the two manipulations.

Neurally, we observed no interaction effects between our two syntactic dependency manipulations. Rather, we first saw a likely syntactic effect of manipulating ARG followed by two later effects of SYN, which may or may not be syntactic in nature. The separation in time, coupled with their distinct spatial localizations, first and foremost implies that ARG and SYN hinge on different underlying mechanisms and therefore runs counter to the hypothesis proposing a common neural hub for resolving syntactic dependencies. Second, this specific temporal ordering supports

an account where syntactic dependencies low in the tree are resolved before those higher in the syntactic tree; while the manipulation of ARG pertains to the lower-level VP domain, the manipulation of SYN involves permutation of the higher-level CP domain. This is in line with predictions from the so-called phase theory of theoretical linguistics (see, e.g., Chomsky (2000)). Further investigations of different aspects of syntactic structure building using, e.g., RPVP may provide illuminating insights regarding the extent to which language processing reflects aspects of hierarchical tree structure divorced from left-to-right parsing when the full sentence is available all at once.

CONCLUSION

What are the neural correlates of syntactic dependencies when dissociated from the differential working memory costs and the lexico-semantic differences that typically accompany research on dependencies? Here we combined properties of Danish syntax with Rapid Parallel Visual Presentation (RPVP) and a simple matching task to address these challenges in a study varying the type (syntactic frame: declarative, yes/no question; verb argument structure: unergative, unaccusative, alternating unaccusative) and number of syntactic dependencies in two-word sentences. Like prior RPVP studies, we found behavioural and electrophysiological "Sentence Superiority Effects", realised as faster and more accurate responses for sentences than lists controls and a left fronto-temporal activity increase (231–407ms) for sentences. This is the first report of Sentence Superiority Effects for such minimal structures. Our syntactic manipulations induced several right-lateral effects—first of verb argument structure (259–375ms) and later of syntactic frame (500–723ms)—the temporal ordering of which suggests hierarchically rather than linearly structured sentence processing. Interestingly, none of our syntactic dependency effects localised in traditional syntactic

hubs like the left inferior frontal gyrus or the left posterior temporal lobe. The neurobiology of displacement may thus differ significantly from conventional perspectives when isolated from covarying factors typically associated with serial stimulus presentation. Together, our results underscore the swift and automatic nature of the language system that—based on input presented for just a few hundred milliseconds—can generate representations sophisticated enough to elicit differential neural responses to superficially similar but linguistically distinct stimuli.

ACKNOWLEDGEMENTS

This work was supported by award G1001 from NYUAD Institute, New York University Abu Dhabi (LP). We thank Alec Marantz and Ailís Cournane for comments on earlier versions of this manuscript and the members of the Neuroscience of Language Lab at NYU for helpful discussion and feedback throughout.

CONFLICTS OF INTEREST

The authors report no conflicts of interest.

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BOX 1

Box 1. Example sentences from Danish illustrating some of the constituents that may occupy the first position in main clauses.

<u>Subject in first position</u>
Hun vandt heldigvis maratonet.
She won luckily marathon-the.
"Luckily, she won the marathon."

<u>Object in first position</u>
Maratonet vandt hun heldigvis.
Marathon-the won she luckily.
"Luckily, she won the marathon."

<u>Adverb in first position</u>
Heldigvis vandt hun maratonet.
Luckily won she marathon-the.
"Luckily, she won the marathon."

<u>Embedded clause in first position</u>
Selvom hun vågnede for sent, vandt hun heldigvis maratonet.
Even-though she awoke too late, won she luckily marathon-the.
"Even though she woke up too late, she luckily won the marathon."

BOX 2

Box 2. Diagnostics used to classify verbs as unergative, unaccusative, or alternating unaccusative.

Verbs were classified as unergative (i) if they employed the auxiliary *have* ("to have") in the perfect, (ii) if they could occur with a reflexive pronoun in resultative constructions, and (iii) if they could occur in impersonal passive constructions. Additionally, unergative verbs had to fail (iv), (v), and (vi).

(i) *Pigen har festet.*
"The girl has partied."
(ii) *Pigen festede sig selv træt.*
"The girl partied herself tired."
(iii) *Der festes.*
"Someone is partying."
(iv) * *Den festede pige.*
"The partied girl."
(v) * *Pigen festede en fest.*
"The girl partied a party."
(vi) * *Pigen blev festet.*
"The girl was partied."

Verbs were classified as unaccusative (i) if they employed the auxiliary *være* ("to be") in the perfect, and (iv) if past participle forms could be used as nominal modifiers. Additionally, unaccusative verbs had to fail (ii), (iii), (v), and (vi).

(i) *Pigen er vågnet.*
"The girl is awoken."
(ii) * *Pigen vågnede sig selv frisk.*
(iii) * *Der vågnes.*
(iv) *Den vågne pige.*
(v) * *Pigen vågnede en kat.*
(vi) * *Pigen blev vågnet.*

Verbs were classified as alternating unaccusative (i) if they could take either auxiliary in the perfect, (iii) if they could occur in impersonal passive constructions, (iv) if past participle forms could be used as nominal modifiers, (v) if they could occur with direct objects, and (vi) if they could undergo passivization. Alternating unaccusative verbs generally did not fare well with reflexive pronouns in resultative constructions as in (ii).

(i) a. *Pigen er tørret.*
"The girl is dried."
b. *Pigen har tørret blusen.*
"The girl has dried the shirt."
(ii) ? *Pigen tørrede sig selv varm.*
(iii) *Der tørres.*
(iv) *Den tørrede pige.*
(v) *Pigen tørrede en bluse.*
(vi) *Pigen blev tørret.*

TABLE 1

Table 1. Lexical characteristics of the different verb types. Mean values for each measure are reported with SD in parentheses. ARG = verb argument structure.

ARG	Letters	Syllables	Morphemes	Phonemes	Frequency
Unergative	7.78 (1.09)	3.33 (0.71)	2.00 (0.00)	7.33 (0.87)	1137.44 (1923.77)
Unaccusative	8.56 (1.13)	3.22 (0.67)	2.44 (0.53)	7.89 (1.05)	1028.56 (1487.93)
Alternating unaccusative	7.33 (0.50)	3.00 (0.00)	2.00 (0.00)	7.11 (0.78)	1231.00 (1046.02)

TABLE 2

Table 2. Results of likelihood ratio tests for linear mixed-effects regression models for response times and accuracies for the entire dataset. COMP: composition; SYN: syntactic frame; ARG: verb argument structure; TASK: match/mismatch trial.

		Response time		Accuracy	
	df	χ^2	*p* value	χ^2	*p* value
COMP	1	108.78	< 0.001	17.73	< 0.001
SYN	1	7.98	0.005	0.58	0.447
ARG	2	20.81	< 0.001	5.20	0.074
TASK	1	290.84	< 0.001	7.52	0.006
COMP × SYN	1	0.08	0.784	0.09	0.766
COMP × ARG	2	5.64	0.060	2.21	0.331
COMP × TASK	1	4.68	0.030	1.69	0.193
SYN × ARG	2	3.22	0.200	0.69	0.707
SYN × TASK	1	10.63	0.001	2.93	0.087
ARG × TASK	2	3.71	0.156	4.32	0.115
COMP × SYN × ARG	2	0.68	0.713	6.11	0.047
COMP × SYN × TASK	1	1.78	0.183	1.96	0.162
COMP × ARG × TASK	2	0.19	0.911	1.61	0.448
SYN × ARG × TASK	2	5.10	0.078	4.26	0.119
COMP × SYN × ARG × TASK	2	0.28	0.867	6.72	0.035

FIGURE 1

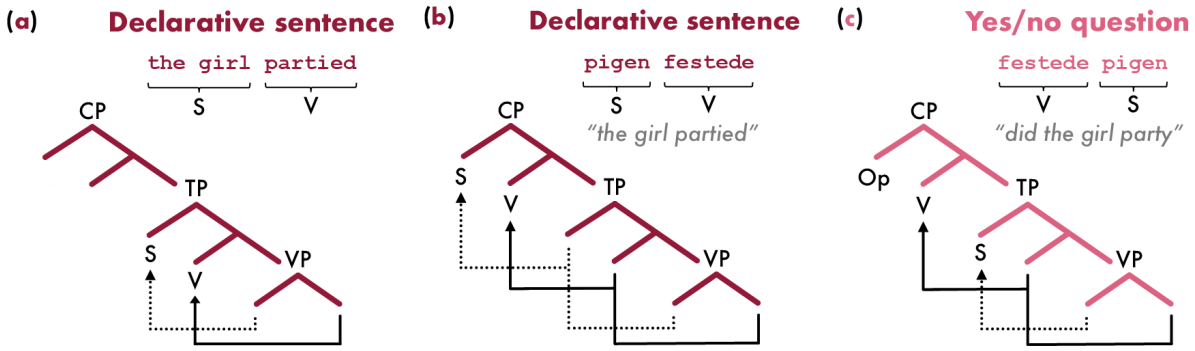
(a)
Declarative sentence
the girl partied
S
V
CP
TP
S
V
VP
(b)
Declarative sentence
pigen festede
S
V
"the girl partied"
CP
S
V
TP
VP
(c)
Yes/no question
festede pigen
V
S
"did the girl party"
CP
Op
V
TP
S
VP

FIGURE 2

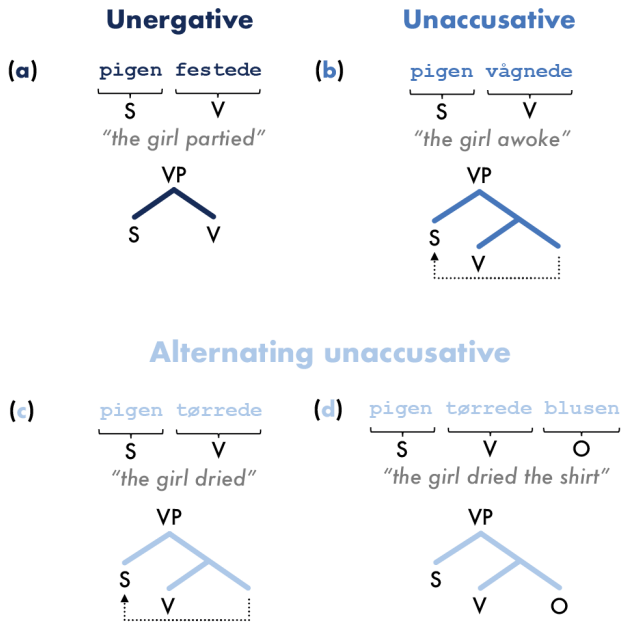
Unergative
Unaccusative
(a)
pigen festede
S V
"the girl partied"
VP
S V
(b)
pigen vågnede
S V
"the girl awoke"
VP
S V
Alternating unaccusative
(c)
pigen tørrede
S V
"the girl dried"
VP
S V
(d)
pigen tørrede blusen
S V O
"the girl dried the shirt"
VP
S V O

FIGURE 3

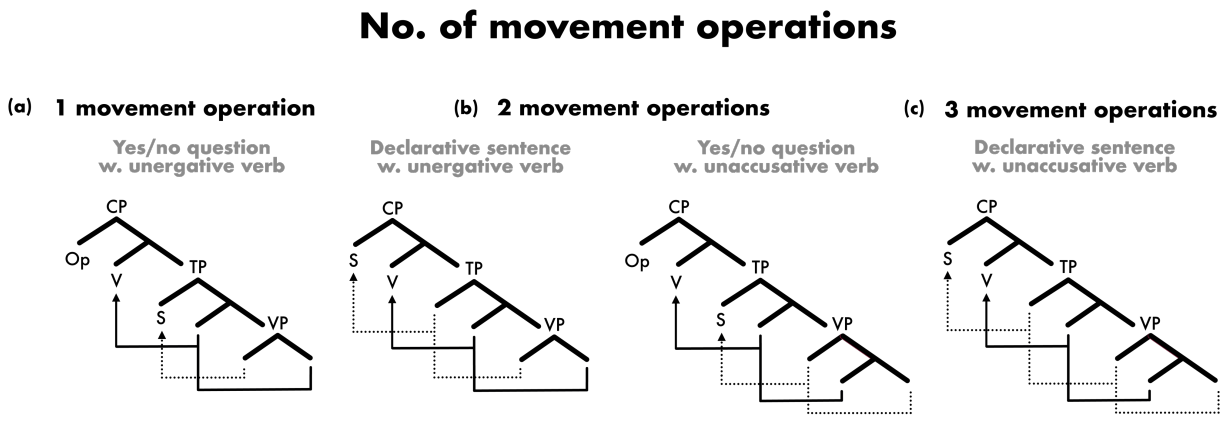
No. of movement operations
(a) 1 movement operation
Yes/no question
w. unergative verb
CP
Op
V
TP
S
VP
(b) 2 movement operations
Declarative sentence
w. unergative verb
CP
S
V
TP
VP
Yes/no question
w. unaccusative verb
CP
Op
V
TP
S
VP
(c) 3 movement operations
Declarative sentence
w. unaccusative verb
CP
S
V
TP
VP

FIGURE 4

(a)

Composition (**COMP**)	Syntactic frame (**SYN**)	Argument structure (**ARG**)	Example	Gloss
Sentence	Declarative	Unergative	pigen festede	*'the girl partied'*
List	Declarative	Unergative	udgav festede	*'published partied'*
Sentence	Yes/no question	Unergative	festede pigen	*'did the girl party'*
List	Yes/no question	Unergative	festede udgav	*'partied published'*
Sentence	Declarative	Unaccusative	pigen vågnede	*'the girl awoke'*
List	Declarative	Unaccusative	udgav vågnede	*'published awoke'*
Sentence	Yes/no question	Unaccusative	vågnede pigen	*'did the girl awake'*
List	Yes/no question	Unaccusative	vågnede udgav	*'awoke published'*
Sentence	Declarative	Alternating unaccusative	pigen tørrede	*'the girl dried'*
List	Declarative	Alternating unaccusative	udgav tørrede	*'published dried'*
Sentence	Yes/no question	Alternating unaccusative	tørrede pigen	*'did the girl dry'*
List	Yes/no question	Alternating unaccusative	tørrede udgav	*'dried published'*

(b)

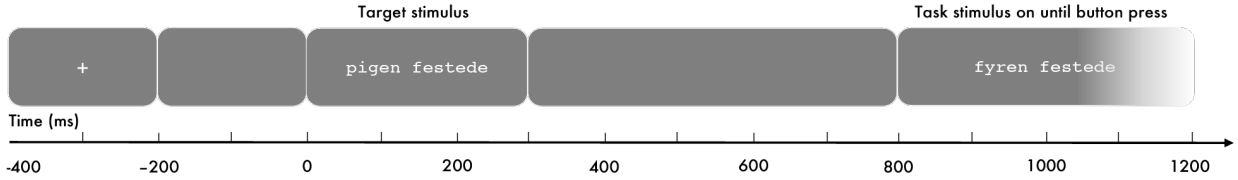

FIGURE 5

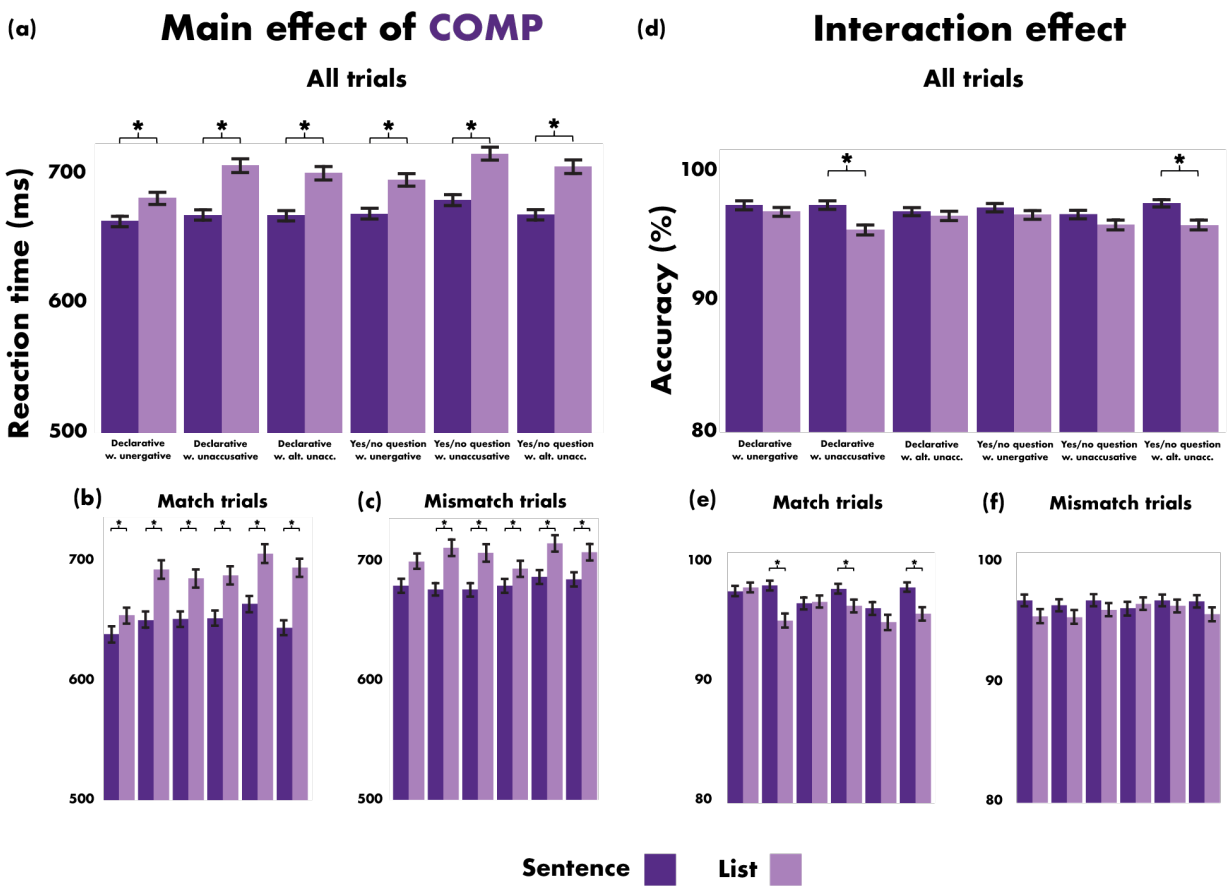
(a)
Main effect of COMP
All trials
Reaction time (ms)
700
600
500
Declarative w. unergative
Declarative w. unaccusative
Declarative w. alt. unacc.
Yes/no question w. unergative
Yes/no question w. unaccusative
Yes/no question w. alt. unacc.
(b)
Match trials
(c)
Mismatch trials
(d)
Interaction effect
All trials
Accuracy (%)
100
90
80
(e)
Match trials
(f)
Mismatch trials
Sentence
List

FIGURE 6

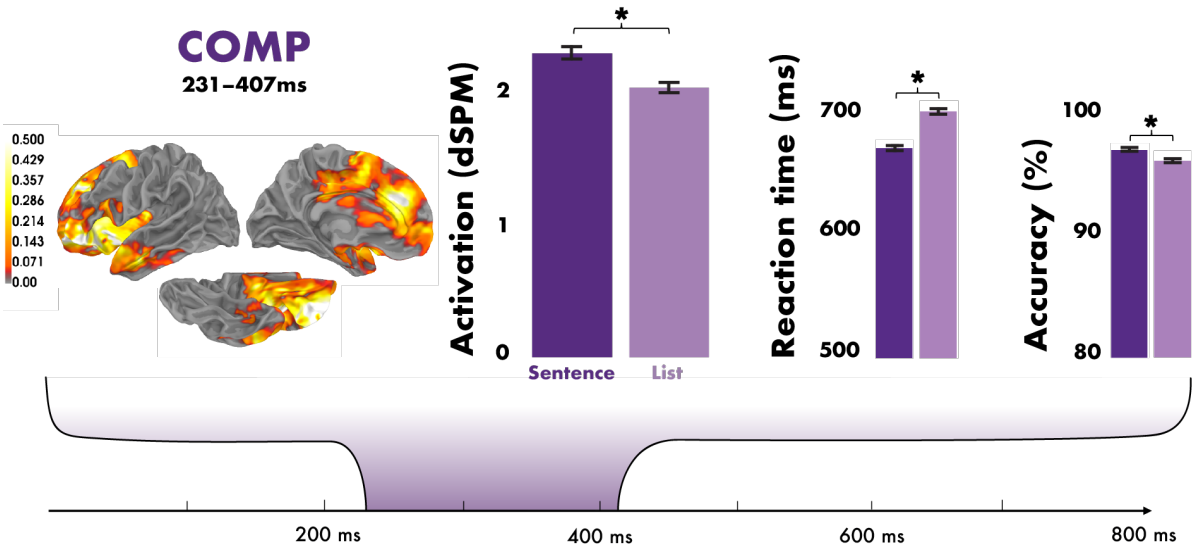
COMP
231–407ms
0.500
0.429
0.357
0.286
0.214
0.143
0.071
0.00
Activation (dSPM)
2
1
0
Sentence
List
*
Reaction time (ms)
700
600
500
*
Accuracy (%)
100
90
80
*
200 ms
400 ms
600 ms
800 ms

FIGURE 7

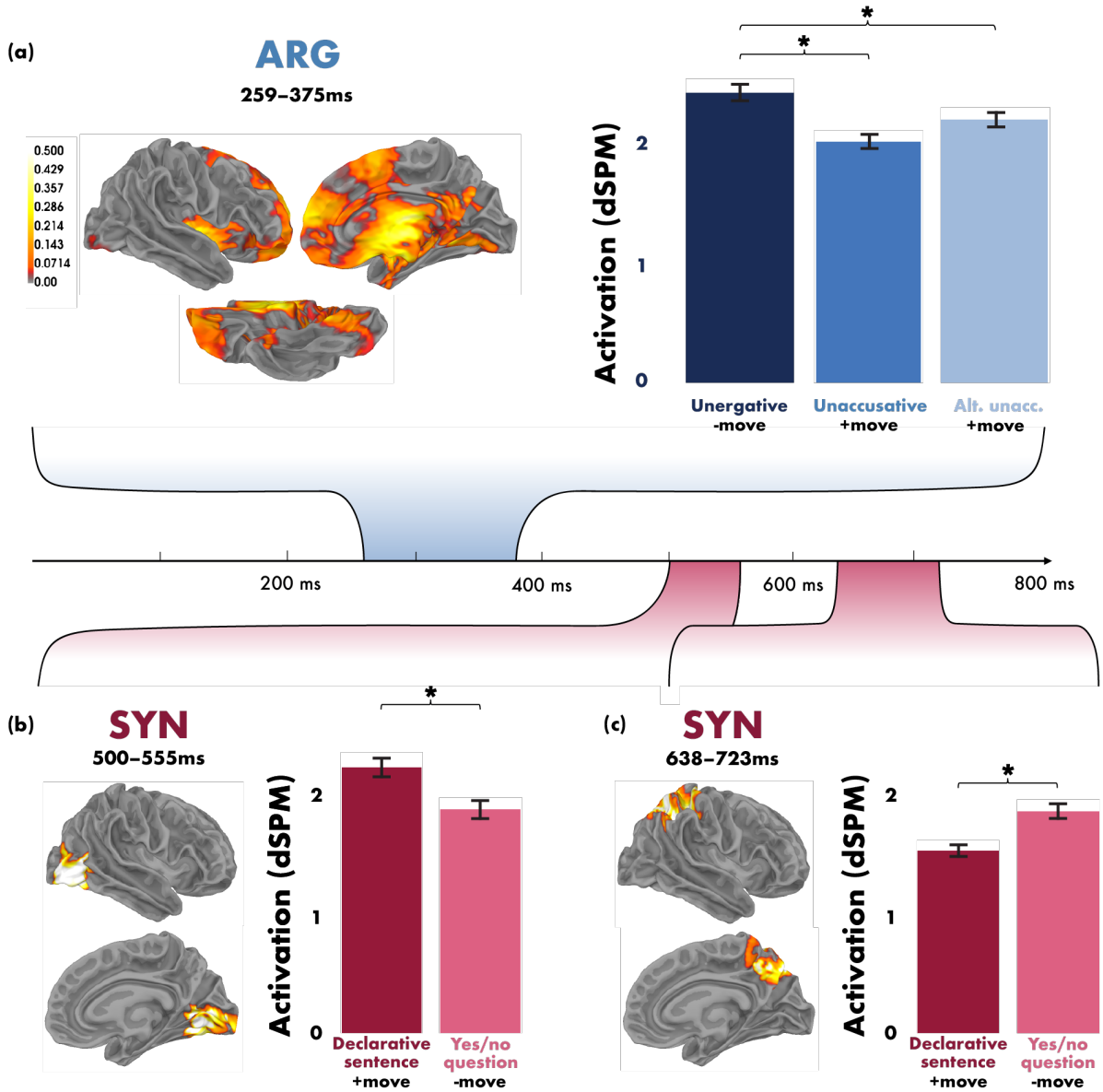
(a)
ARG
259–375ms
0.500
0.429
0.357
0.286
0.214
0.143
0.0714
0.00
Activation (dSPM)
0
1
2
*
*
Unergative
-move
Unaccusative
+move
Alt. unacc.
+move
200 ms
400 ms
600 ms
800 ms
(b)
SYN
500–555ms
Activation (dSPM)
0
1
2
*
Declarative
sentence
+move
Yes/no
question
-move
(c)
SYN
638–723ms
Activation (dSPM)
0
1
2
*
Declarative
sentence
+move
Yes/no
question
-move

FIGURE CAPTIONS

Figure 1. Simplified tree diagrams to illustrate the differences between (**a**) English declarative sentences, (**b**) Danish declarative sentences, and (**c**) Danish yes/no questions. Arrows indicate displacement of elements from positions lower in the tree (syntactic dependencies). S: subject; V: verb; Op: empty operator; CP: complementiser phrase; TP: tense phrase; VP: verb phrase.

Figure 2. Simplified tree diagrams illustrating the different verb argument structures for (**a**) unergative verbs, (**b**) unaccusative verbs, as well as the (**c**) intransitive and (**d**) transitive forms of alternating unaccusative verbs. Note that all four structures must necessarily be embedded in complete CPs (see Figure 3 for examples). Arrows indicate displacement of elements from positions lower in the tree (syntactic dependencies). S: subject; V: verb; O: object; CP: complementiser phrase; VP: verb phrase.

Figure 3. Simplified tree diagrams illustrating the interaction between manipulations of syntactic frame and verb argument structure, quantified as the number of movement operations between the different conditions. (**a**) Yes/no question with unergative verb (1 movement operation). (**b**) Declarative sentence with unergative verb and yes/no question with unaccusative verb (both 2 movement operations). (**c**) Declarative sentence with unaccusative verb (3 movement operations). Sentences with alternating unaccusative verbs (not depicted) pattern as those with unaccusative verbs. Arrows indicate displacement of elements from positions lower in the tree (syntactic dependencies). S: subject; V: verb; Op: empty operator; CP: complementiser phrase; TP: tense phrase; VP: verb phrase.

Figure 4. Design table and trial structure. (**a**) Full factorial design with factors composition (COMP), syntactic frame (SYN), and verb argument structure (ARG) alongside example trials for each condition. (**b**) Trial structure illustrating a mismatch trial; the target stimulus and task stimulus differ from each other by one word. The width of the grey boxes indicates length of time on screen.

Figure 5. Instances of a behavioural Sentence Superiority Effect plotted for the entire factorial design. On the left, a significant main effect of COMP for response times across (**a**) all trials, (**b**) match trials, and (**c**) mismatch trials. On the right, a significant three-way interaction between COMP, SYN, and ARG across (**d**) all trials, (**e**) match trials, and (**f**) mismatch trials. COMP: composition; SYN: syntactic frame; ARG: verb argument structure.

Figure 6. An instance of the Sentence Superiority Effect. Neurally, it manifested with a broad fronto-temporal distribution in the left hemisphere from ~230–405ms post stimulus onset, with increased activity to sentences over lists (left). Response times (middle) and accuracies (right) also showed facilitated processing for sentences compared to lists. COMP: composition; * = $p < 0.05$ corr.

Figure 7. Significant effects of manipulating syntactic dependencies. (**a**) A main effect of ARG was found in right fronto-medial areas from ~260–375ms post stimulus onset, with t-tests showing that sentences with unergative verbs elicited significantly more activity than sentences with unaccusative (284–364ms; $p < 0.001$) and alternating unaccusative (326–364ms; $p = 0.0178$) verbs. Post-hoc analyses on the full dataset and the lists in isolation did not replicate this main effect, which suggests that it does not stem from verb-level semantics. (**b**) The first effect of SYN localised in right occipital areas from ~500–555ms, with declarative sentences eliciting more activity than yes/no questions, while (**c**) the second effect of SYN localised in right parietal areas from ~640–725ms with the reverse directionality. A post-hoc analysis on the list stimuli did not replicate these effects, and they are therefore likely to not simply reflect perceptual differences as a result of the word order swap. ARG: verb argument structure; SYN: syntactic frame; * = $p < 0.05$ corr.