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Task-free auditory EEG paradigm for probing multiple levels of speech processing in the brain

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Abstract

While previous studies on language processing highlighted several ERP components in relation to specific stages of sound and speech processing, no study has yet combined them to obtain a comprehensive picture of language abilities in a single session. Here, we propose a novel task-free paradigm aimed at assessing multiple levels of speech processing by combining various speech and nonspeech sounds in an adaptation of a multifeature passive oddball design. We recorded EEG in healthy adult participants, who were presented with these sounds in the absence of sound-directed attention while being engaged in a primary visual task. This produced a range of responses indexing various levels of sound processing and language comprehension: (a) P1-N1 complex, indexing obligatory auditory processing; (b) P3-like dynamics associated with involuntary attention allocation for unusual sounds; (c) enhanced responses for native speech (as opposed to nonnative phonemes) from ~50 ms from phoneme onset, indicating phonological processing; (d) amplitude advantage for familiar real words as opposed to meaningless pseudowords, indexing automatic lexical access; (e) topographic distribution differences in the cortical activation of action verbs versus concrete nouns, likely linked with the processing of lexical semantics. These multiple indices of speech-sound processing were acquired in a single attention-free setup that does not require any task or subject cooperation; subject to future research, the present protocol may potentially be developed into a useful tool for assessing the status of auditory and linguistic functions in uncooperative or unresponsive participants, including a range of clinical or developmental populations.

KEYWORDS

auditory system, EEG, ERP, evoked potentials, language, speech

1 | INTRODUCTION

Psychological or clinical assessments of various populations often have to rely on behavioral methods, requiring overt responses from the participants. Often, however, due to various impairments or specific situations, patients/participants may be unable to properly report their experiences, dictating the need for an objective tool to assess their neurocognitive status in the absence of an active task. This is particularly true when the patient's speech communication ability is compromised, and thus a need arises to probe the neural mechanisms of speech processing in a participant-friendly, task-free fashion.

Previous research using noninvasive neurophysiological tools such as EEG has demonstrated that specific brain

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responses associated with auditory feature extraction or attentional and language processes could be elicited in passive conditions, where the participant's active engagement in the listening task is not required. Research on the time course of sound and speech processing has highlighted several responses taken to index specific steps of language parsing, which could be particularly relevant in assessing language functions in a task-free manner. For instance, the P1-N1 complex, including the P1 (P50) and the N1 (N100) obligatory auditory responses (Davis & Zerlin, 1966; Näätänen & Picton, 1987), has become a well-known marker of cortical auditory processing on account of its high reproducibility (Boutros et al., 2009; Conley, Michalewski, & Starr, 1999; Moura, Triñanes-Pego, & Carrillo-de-la-Peña, 2010; Näätänen & Picton, 1987; Picton & Hillyard, 1974).

Further, for probing perceptual processes related to auditory information, some studies have investigated attention allocation in the auditory modality—this is typically done by varying salient sound features such as intensity, complexity, or even emotional valence (Alho et al., 1998; Meinhardt & Pekrun, 2003; White & Stuart, 2011). The P300, a positive deflection peaking at around 300 ms after the onset of rare salient events in a stimulus sequence, has been described as an index of the auditory attention function (Grossi & Coch, 2005; Polich, 2007). The P300 is typically subdivided into subcomponents, the earliest of which, the P3a, has been linked to automatic attention shifts to novel sounds, which may precede behavioral orienting and subsequent reaction to a potentially important external event (Friedman, Cycowicz, & Gaeta, 2001; Friedman, Goldman, Stern, & Brown, 2009; Simons, Graham, Miles, & Chen, 2001). The P3a thus reflects an important index of auditory cognition; crucially, it is elicited in passive task-free designs, and is thus also a good candidate for a task-free assessment of auditory processes.

At the level of speech-specific phonetic and phonological information processing, an important step is that of feature extraction, whose impairment has been associated with language deficits, such as dyslexia (Ylinen & Kujala, 2015). Responses in the 50–240 ms range have been attributed to the activation of phoneme- and syllable-specific representations for native speech. For instance, native syllables produce stronger activation than matched nonspeech sounds (Kuuluvainen et al., 2014; Palva et al., 2002; Shtyrov, Kujala, Palva, Ilmoniemi, & Näätänen, 2000), and native vowels show an enhancement over nonnative ones (Näätänen et al., 1997). Such an enhancement has been documented in nonattended oddball designs and has been attributed to the automatic activation of long-term memory traces for native phonology.

In addition to extracting basic acoustic and phonetic features, language comprehension requires processing of more complex information of different types, such as lexical (pertinent to word representations), semantic (meaning), and syntactic (grammar), among others. All of these processing levels have been linked to different electrophysiological responses that, in turn, could potentially be used to probe linguistic processing in the brain (see, e.g., reviews by Friederici, 2002; Pulvermüller, Shtyrov, & Hauk, 2009).

A crucial step in spoken language parsing is lexical processing, during which a phonological form is matched to an entry in the mental lexicon. While studies targeting lexical access to words within sentential contexts have reported lexical processes within the 200-ms range (Hagoort & Brown, 2000; Van den Brink, Brown, & Hagoort, 2001), experiments using lexical decision tasks in attended conditions have reported a component peaking at around 350 ms after word onset, understood as indexing automatic lexical processing (Embick, Hackl, Schaeffer, Kelepir, & Marantz, 2001; Pylkkänen & Marantz, 2003; Pylkkänen, Stringfellow, & Marantz, 2002) and possibly being part of the broader N400 response. Lexicality effects were also found in the context of oddball paradigms where participants were presented with real words and meaningless pseudowords in passive unattended settings. These setups have typically elicited the so-called lexical enhancement—larger or more robust mass neuronal responses to familiar real words than to meaningless pseudowords—that was suggested to reflect the automatic activation of preexisting long-term memory traces for real words (Garagnani, Shtyrov, & Pulvermüller, 2009; Kimppa, Kujala, Leminen, Vainio, & Shtyrov, 2015; MacGregor, Pulvermüller, Van Casteren, & Shtyrov, 2012; Shtyrov, Kimppa, Pulvermüller, & Kujala, 2011; Shtyrov, Kujala, & Pulvermüller, 2009; Shtyrov & Pulvermüller, 2007). The possibility of recording such language-specific brain activity in the absence of an active task or even attention makes this approach another potential candidate for objective assessment of neurolinguistic status.

Yet another linguistic information type, often distinguished from the lexical level, is semantics (i.e., access of meaning per se), also reflected in ERP responses. One strand of research into the neural mechanisms underlying semantic processing argues that comprehension of a given word involves the specific modality associated with its semantics, causing the activation of the brain circuits responsible for the modality in question (Grisoni, Dreyer, & Pulvermüller, 2016). This so-called grounded cognition approach suggests that, in addition to the core language systems, the processing of action-related words or sounds involves the motor cortices, while vision or audition-related words engage the respective sensory systems. Frontal motor cortex activity during the processing of action-related words was indeed found in some studies (Hauk, Johnsrude, & Pulvermüller, 2004; Hauk, Shtyrov, & Pulvermüller, 2006), while object-related concrete nouns lead to temporo-occipital activation (Gainotti, 2004; Hillis, Tuffiash, Wityk, & Barker, 2002; Pulvermüller, Lutzenberger, & Preissl, 1999). The fact that the topographic distribution of action- and object-related word ERPs diverge, where the former shows a more frontal distribution of the brain activity and the latter exhibits a more posterior distribution (Hauk et al., 2004; Moseley, Pulvermüller, & Shtyrov, 2013; Pulvermüller, Härle, & Hummel, 2001; Raposo, Moss, Stamatakis, & Tyler, 2009), makes it possible to use these ERP topographies as a correlate of word meaning comprehension without relying on any overt semantic judgment task. This is particularly crucial as such semantically specific activation can be found in non-attend oddball designs using passive listening with no focused attention[1] on the language input (Pulvermüller, Shtyrov, & Ilmoniemi, 2005; Shtyrov, Hauk, & Pulvermüller, 2004a).

Finally, the ELAN response (early left anterior negativity), occurring between 100 and 300 ms after syntactic violation, is proposed to reflect early automatic syntactic processing independent of focused attention. The ELAN is reported to be sensitive to word category and phrase structure rule errors as well as morphosyntactic violations (Friederici, 2002; Hahne & Friederici, 1999). A response highly similar to ELAN is the so-called syntactic mismatch negativity (sMMN), which shows similar latency, scalp distribution, and cortical sources when syntactic violations are presented in an oddball paradigm among grammatically correct stimuli (Hanna et al., 2014; Hasting, Kotz, & Friederici, 2007). Unlike later syntactic ERPs (such as P600), both ELAN and sMMN responses can be recorded in the absence of tasks and focused attention on the sound stream, and it has been suggested that the two are underpinned by the same automatic syntax parsing processes in the brain (Pulvermüller & Shtyrov, 2003; Pulvermüller, Shtyrov, Hasting, & Carlyon, 2008; Shtyrov, Pulvermüller, Näätänen, & Ilmoniemi, 2003).

Methodologically, the auditory processes mentioned above can be addressed through the use of oddball paradigms in which a sequence consisting of the same repetitive (so-called standard) stimulus is occasionally interrupted by a different (deviant) stimulus item in the absence of any task or focused attention to stimuli. Usually, standard-deviant contrasts are then used to calculate the mismatch negativity (MMN) response, a difference response that has shown sensitivity to various types of auditory information. Studies employing this paradigm have provided data on neural underpinnings of automatic change discrimination by auditory sensory systems (Näätänen, 2003; Näätänen, Paavilainen, Rinne, & Alho, 2007), automatic attention allocation as reflected by P3a (Friedman et al., 2009; Simons et al., 2001), activation of long-term memory traces for spoken words (Pulvermüller, Kujala et al., 2001; Shtyrov, Osswald, & Pulvermüller, 2008), semantically specific word activations (Pulvermüller et al., 2005; Shtyrov et al., 2004a), as well as automatic morphological (Bakker, Takashima, Van Hell, Janzen, & McQueen, 2015; Hanna & Pulvermüller, 2014; Leminen, Leminen, Kujala, & Shtyrov, 2013; MacGregor & Shtyrov, 2013) and (morpho)syntactic processing (Hanna et al., 2014; Hasting et al., 2007). Particular advantages of such designs include their independence of an active attention-demanding task, a possibility to balance auditory contrasts while manipulating linguistic contexts, and a focus on small sets of well-controlled stimuli that enables close scrutiny of transient differences in response dynamics (Shtyrov, 2010).

One modification of the oddball paradigm—the so-called multifeature design—provides a particularly attractive way to address multiple stimulus properties in a single sequence. It does so by presenting standard stimuli in every second position in the auditory sequence, while all other positions are equiprobably distributed between multiple deviants of different types (Näätänen, Pakarinen, Rinne, & Takegata, 2004). This approach allows saving time while collecting information on a wider range of auditory processes than possible in traditional oddball sequences consisting mostly of standards. While it was initially developed for nonspeech stimuli, it has more recently been employed for studying phonological, lexical, morphosyntactic, and other effects. We have therefore adopted the multifeature design for this study and employed different acoustic and linguistic stimulus modifications, with an aim to develop a paradigm that could simultaneously quantify a range of speech-related processes: (a) basic auditory processing of sounds, (b) auditory attention allocation, (c) phonetic/phonological processing of native speech sounds, (d) lexical memory trace activation for native words, (e) processing of word meaning (semantics), and (f) (morpho)syntactic processing. This was achieved, respectively, through (a) analyzing obligatory responses to all different sound types, (b) including unexpected salient (so-called novel) nonspeech sounds in the speech stimulus stream, (c) contrasting native and nonnative phonemes, (d) measuring real words against similar meaningless pseudowords, (e) comparing the topographical distribution of responses to words with different meanings, and (f) contrasting (morpho)syntactically correct and incorrect combinations.

All of these different stimuli were maximally controlled for their auditory and psycholinguistic features and presented in a passive design without any stimulus-related tasks, while the subjects' attention was diverted away from the auditory input. We hypothesized that (a) acoustic processing of all sounds would be reflected by a P1-N1 complex response to sound onsets, while (b) novel sounds would lead to a P3a, indicating involuntary allocation of attention caused by the occurrence of a novel stimulus (Debener, Makeig, Delorme, & Engel, 2005), phonological and lexical processing would produce a (c) phonological and a (d) lexical ERP response enhancement for native phonemes and words, respectively (Kujala, Alho, Service, Ilmoniemi, & Connolly, 2004; Shtyrov, Nikulin, & Pulvermüller, 2010; Shtyrov et

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[1] Another well-known ERP marker of semantic processing, the N400 response, can be elicited by potentially meaningful stimuli (e.g., words or images), and is thought to reflect access to representations, long-term semantic memory, as well as context integration (Kutas & Federmeier, 2011). The N400, however, typically involves active tasks, limiting its applicability in an attention-free manner.

al., 2012), whereas (e) semantic distinctions would yield differences in the activation of the cortical networks (i.e., a more frontal activation including motor areas for action words and a more posterior activation including visual areas for visual words; Hauk et al., 2004). We also expected (f) morphosyntactic violations in the word stimuli to evoke an ELAN-like response (Friederici, Pfeifer, & Hahne, 1993). Note that, while we did adopt the multifeature paradigm, we did not calculate MMN per se. Considering the very diverse properties of our deviant stimuli, which were optimized for direct contrasts rather than for calculating the MMNs, a subtraction did not seem practical (and, further, would reduce signal-to-noise ratio, SNR). Instead, we directly compared responses to different stimulus types, in line with conventional ERP approaches. Here, we report the results of our initial testing of this approach in healthy adult volunteers.

2 | METHOD

2.1 | Participants

Twenty-one healthy right-handed (handedness assessed using Oldfield, 1971) native speakers of Danish (age range 19–33, mean 25.6 years, 8 male) with normal hearing and no record of neurological impairment were recruited for the experiment, of which three were excluded due to low signal quality or technical problems. The final participant pool thus totalled 18 participants. The experiment was evaluated by the Central Denmark Region Committees on Health Research Ethics and conducted in accordance with the Helsinki Declaration. All subjects provided written consent and were remunerated for their participation.

2.2 | Stimuli

Due to the variety of features we intended to test, we opted for a multifeature oddball paradigm, a variation of the oddball design with a standard accounting for half of the total stimuli and five deviants occurring with a 10% probability each, as it makes it possible to include several stimulus types while minimizing the experimental time (Näätänen et al., 2004). Since we addressed six different levels of speech processing, we chose stimulus items that would enable us to contrast a combination of different linguistic phenomena, adding up to six contrasts in total, while controlling for acoustic features (see Figure 1 for examples of the stimuli used). We thus selected to use as standard stimuli four main spoken items which (a) belonged to different linguistic categories (verb, noun, real word, and pseudoword), (b) were close in terms of phonology so we could compare them

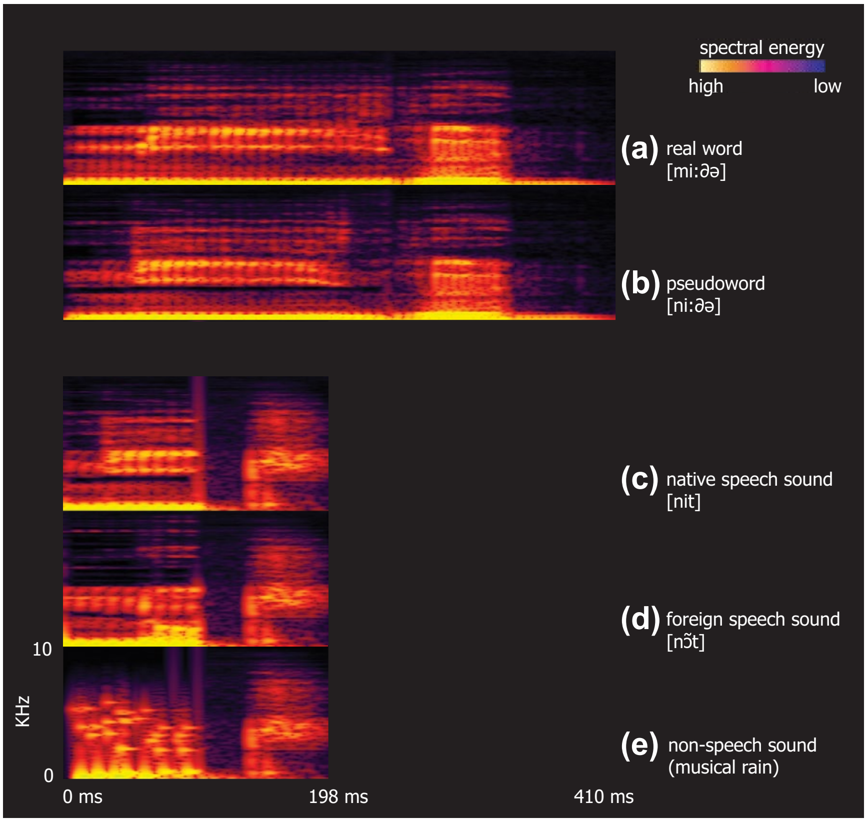

FIGURE 1 Examples of spectrograms of spoken stimuli used in the experiment. Different stimuli were matched for their acoustic features with the items they are contrasted against (a,b) real words versus pseudowords; (c,d) native versus foreign speech items; and (c–e) speech versus nonspeech items

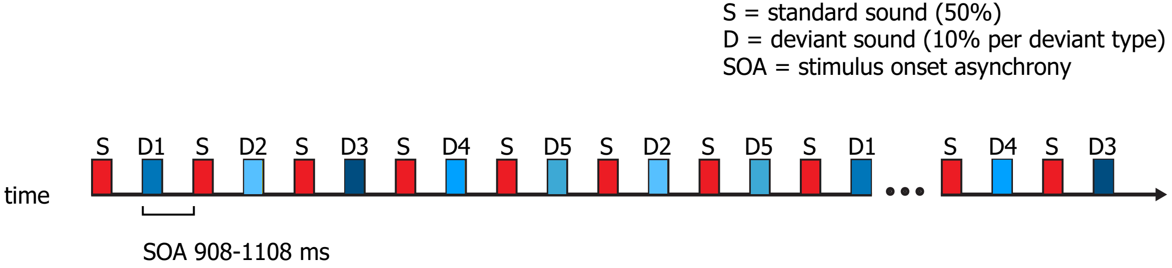

FIGURE 2 Schematic illustration of stimulus sequences within an experimental block. Standards (in red) make up half the stimuli. The five different hues of blue represent the five different types of deviants, each occurring at a 10% rate. SOA was varied between 908 and 1,108 ms

directly with minimal acoustic/phonetic confounds, and (c) could be modified morphosyntactically in the exact same way and nonetheless exhibit different linguistic properties (e.g., syntactically correct vs. incorrect) so that we could test the very same contrasts in different linguistic contexts. Following the multifeature oddball design (see Figure 2), each standard was complemented by five deviants whose linguistic features could be compared across blocks. We targeted lexical and semantic processes using the base forms presented as standards. By employing different deviants, we aimed to elicit syntactical, phonological, and automatic attentional processes. In order to compare deviants and standards across blocks, we built all standards and all deviants on the exact same model using cross-splicing. This gave rise to disyllabic standard stimuli, which we will call stems in this context, and a range of deviants that were constructed based on these stems.

The stimuli were made based on a digital recording of a male native speaker of Danish in an anechoic chamber (recording bandwidth: 44 kHz, 16-bit, stereo) and manipulated using Adobe Audition CS6 (Adobe Inc., San José, CA). The first and second syllables of our disyllabic stimuli were recorded independently, in order to avoid possible coarticulation effects, and cross-spliced together. The sounds were matched for loudness, with a 1.93 dB drop between the first and the second syllables so that our stimuli sounded as natural as possible, and normalized to have identical power (measured as root-mean-square, RMS). The particular stimulus types are described below.

2.2.1 | Stems: Lexical and semantic processing

Lexical memory trace activation and word meaning processing

In order to create four stems, we selected four syllables, [bi], [mi], [ni], and [gi], matched for their fundamental frequency (215 Hz) and cross-spliced them with the syllable [de] (realized in this type of Danish word as [ðə]) yielding four sounds phonologically similar but differing in their lexical and semantic statuses: action-related verb *bide* (to bite), concrete noun *mide* (a mite), nonaction verb *gide* (to bother), and a meaningless pseudoword *nide* (see Figure 1 and Table 1). We subsequently modified these stems to create deviants in accordance with our different experimental conditions.

2.2.2 | Deviants: Syntactic, phonological, basic auditory, and automatic attention allocation processes

Morphosyntax

We took advantage of Danish morphology and the fact that the morphemes *-(e)t* and *-(e)n* can be used to express the regular past participle of verbs and definiteness on common nouns. We cross-spliced all four stems with these two morphemes in order to obtain words either violating or respecting rules of Danish morphology such that the exact same phonemes completed syntactic or asyntactic forms in a counterbalanced fashion (see "Syntax, Regular" in Table 1). This would thus enable us to compare ERPs to the inflected items based on their congruence or incongruence, e.g., -(e) n in *miden* vs. **giden*, and -(e)t in *gidet* vs. **midet* (where * indicates a syntactic violation of the stem/affix agreement for either participle conjugation or gender).

The inclusion of an irregular past tense verb *bidt* ([bit]—past participle of *bide*) as part of our stimuli allowed us to use the overregularized verb (**bidet*) as a further violation. To balance for this, we also included phonologically matched words and pseudowords built in similar fashion, [mit] (possessive pronoun, first person, singular), *[git], and [nit] (to rivet, imperative). We thus took the four syllables used to create the stems and shortened the vowel sound, leading to a 106-ms root to which we cross-spliced the morpheme [t] (see "Syntax, Irregular" in Table 1) yielding a set of short monosyllabic items.

Native and nonnative phonology

Using the monomorphemic irregular forms as a model to build the nonnative stimuli, we contrasted native (Danish) and nonnative phonology. Hence, we selected four syllables similar to the stem condition but containing a vowel sound, not present in the Danish phonological system, a vowel similar to the nasal [ɔ̃]. These syllables ([bɔ̃t], [mɔ̃t], [nɔ̃t], and [gɔ̃t]) otherwise matched the native stems in their fundamental frequency

TABLE 1 List of auditory stimuli used in the paradigm

	Stimuli					
		Syntax deviants				
Condition	Stem (frequent standard, 50%)	Regular (10% each)		Irregular (10%)	Nonnative (phonology deviants, 10%)	Nonspeech (MR deviants, 10%)
Action verb	*bide* [biːðə] (bite)	**bidet* [biːðət]	**biden* [biːðən]	*bidt* [bit]	*[bɔ̃t]	*MR[bit]
Nonaction verb	*gide* [giːðə] (bother)	*gidet* [giːðət]	**giden* [giːðən]	**git* [git]	*[gɔ̃t]	*MR[git]
Concrete noun	*mide* [miːðə] (mite)	**midet* [miːðət]	*miden* [miːðən]	*mit* [mit]	*[mɔ̃t]	*MR[mit]
Pseudoword	**nide* [niːðə]	**nidet* [niːðət]	**niden* [niːðən]	*nit* [nit]	*[nɔ̃t]	*MR[nit]

Note. Auditory stimuli are organized by condition (columns) and linguistic category (rows). Meaningless and syntactic items are marked with an asterisk. MR = musical rain.

(215 Hz) and duration (106 ms), and were cross-spliced with the same morpheme [t], yielding four nonnative speech items (see “Nonnative speech” in Table 1). We chose to model the nonnative speech items on the basis of the monosyllabic irregular condition in order to reduce the experimental time and to be able to compare them to acoustically similar, phonologically native speech items. By comparing an average of the four nonnative forms to the average of their four Danish equivalents, this contrast aimed at addressing the potential differences in phonological processing between native and nonnative speech.

Nonspeech sounds

In this condition, in order to assess basic auditory processing and auditory attention allocation, we took the same stems as used in the irregular form and transformed them into the so-called musical rain, a complex sound mimicking the spectral complexity of speech despite having no resemblance to any articulated output (Uppenkamp et al., 2006). In order to create four musical rain items, we extracted the formants of each individual syllable used in the irregular condition (i.e., [bi], [mi], [ni], [gi]) before modifying their pitch by half an octave and randomizing the onset of the formant envelope. To generate the four finite musical rain signals, we randomly put back together the time courses of the formants for each syllable, band-pass filtered (20–24000 Hz) the finite signal for artifacts, and cross-spliced it with the same morpheme [t], leading to four nonspeech sounds with the same overall spectral properties as the original native speech items.

2.3 | Procedure

During the recording, participants were instructed to focus on a silent film while ignoring the sounds, in line with previous experiments on nonattended acoustic and linguistic processing and with a view of developing a paradigm for subjects who cannot cooperate with an active listening task. The experiment took place in an electromagnetically shielded and acoustically attenuated room. The stimuli were presented through in-ear tubes (Etymotic ER-30) binaurally at 50 dB above individual auditory threshold. The stimulus onset asynchrony (SOA, i.e., onset to onset) varied between 908 and 1,108 ms, with a mean of 1,008 ms.

Stimulus presentation was controlled using NBS Presentation software (Neurobehavioral Systems, Inc., Albany, CA). The four different sets of stimuli (with *bide, mide, gide*, and *nide* as standards) were each presented in four short blocks of ~7 min per block. Participants were offered short breaks in between each of the blocks (16 blocks in total) while remaining in place, and the order of the conditions (i.e., the sets of four consecutive blocks) was counterbalanced across participants. Hence, four conditions with four blocks each give a full duration of ~120 min (including a few short breaks).

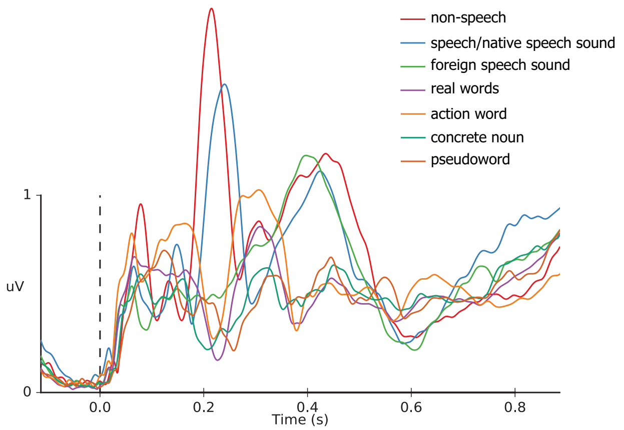

FIGURE 3 Waveforms of the global field power (GFP) for each of the individual contrasts used in the analyses

Each block consisted of 200 standard stimuli (e.g., *bide*) and 200 deviant stimuli distributed over five deviants. Thus, in each block, there were 40 repetitions of any given deviant, totaling 160 exposures to each deviant in each condition. As already described, every second sound was a standard and every other alternate sound was a deviant (Figure 2). The order of the deviants was pseudorandomized so that all five deviants were presented before the order was randomly shuffled anew.

2.4 | EEG recording and preprocessing

EEG data were acquired simultaneously with a 1 kHz sampling rate using a 75-channel custom-layout passive EEG electrode cap (Easycap GmbH, Herrsching, Germany) with built-in Ag-AgCl electrodes placed according to the extended 10-10 system, referenced online to FCz, and connected to an EEG amplifier (Elekta Oy, Helsinki, Finland). Impedances were controlled at the beginning of the recording sessions and were kept under 5 kΩ.

EEG preprocessing and analysis were performed using MNE-Python software package (Gramfort et al., 2014). Continuous data were band-pass filtered offline between 0.1 and 40 Hz, rereferenced to the common average reference, and segmented into 1-s epochs, starting 100 ms before the onset of each stimulus. Trials were baseline corrected (-100–0 ms before the stimulus onset), and eyeblinks and horizontal eye movements were removed from the data using independent component analysis (ICA) as it is implemented in MNE-Python, using the *find_bads_eog* algorithm. All identified electrooculogram components were visually inspected, and in case of under- or overidentification of components, the selection was manually updated. Finally, any remaining trials containing artifacts above or equal to a 150 μV threshold were rejected. Blocks with less than two thirds of the trials remaining after artifact rejection were discarded (which led us to exclude two participants, a third one was excluded due to technical problems during recording), and noisy channels were interpolated. ERPs were generated by averaging accepted trials separately for all conditions, electrodes, and participants.

2.5 | Statistical analysis

For an unbiased choice of temporal analysis intervals, we computed GFPs (global field power, equivalent to computing the standard deviation of the electric potentials at each time point across all electrodes; Skrandies, 1990). We used the group-averaged GFP waveforms calculated across the relevant stimuli and condition contrasts to identify peaks corresponding to the timing of our preselected ERP components (see Figure 3). The peaks identified thus occurred within the time ranges typically reported in the literature for the target ERP components (see Table 2). Crucially, when identifying these peaks, we collapsed (i.e., averaged across) the dimension for which we tested (e.g., pseudoword/real word). As an analysis approach to avoid double-dipping, this process is termed a collapsed localizer by Luck and Gaspelin (2017). Using the latencies of the identified peaks, we calculated 20-ms windowed averages of the ERP amplitudes around the peak of each relevant condition (see Table 2 for a summary of all the contrasts used in the analysis).

We extracted these 20-ms mean amplitudes for each participant from an electrode array covering the frontocentral scalp area where auditory responses are commonly picked up, and used the average of this selection for each condition as our summary values: frontal: F7, F5, F3, F1, Fz, F2, F4, F6, F8; frontocentral: FT7, FC5, FC3, FC1, FC2, FC4, FC6, FT8; central: T7, C5, C3, C1, Cz, C2, C4, C6, T8; centroparietal: TP7, CP5, CP3, CP1, CPz, CP2, CP4, CP6, TP8 (see Figure 4a–d). In the semantic contrast, we hypothesized a difference in posterior-anterior distribution between conditions. We therefore regrouped our electrode selection into two sets: a frontal set comprising the frontal and frontocentral selections, and a parietal set comprising the centroparietal selection as well as a parietal selection: P7, P5, P3, P1, Pz, P2, P4, P6, P8 (see Figure 4e).

To test the basic auditory responses (i.e., the obligatory P1 and N1 components), we performed two one-sample *t* tests comparing their amplitudes against zero. For the remaining contrasts (speech vs. nonspeech, native vs. nonnative sound, real vs. pseudowords, syntactic vs. asyntactic form), since we did not have any a priori hypotheses pertaining to topographical differences in any of the conditions, except for in the semantic condition, we performed paired *t* tests on their amplitudes at the frontocentral scalp area. Finally, for the semantic condition, we performed a repeated measures analysis of variance (ANOVA) with factors condition (action verb vs. concrete noun) and anteriority (frontocentral vs. parietal selection of electrodes). For effect sizes, we report Hedges's *g* for all *t* tests and partial eta squared for the repeated measures ANOVA (Lakens, 2013). All tests were planned a priori and independent of each other, and statistical significance level was set at

TABLE 2 List of contrasts addressed in the analysis

Language level	Contrast	Expected ERP component of interest
(a) Basic auditory processing of sounds	Nonspeech sounds against zero	P1-N1 complex
(b) Auditory attention allocation	Nonspeech novel sounds against matched speech (irregular items in Table 1)	P3a response
(c) Phonetic/phonological processing of native speech sounds	Speech items containing a native vowel (average of all the irregular items in Table 1) against nonwords containing a matched nonnative vowel (average of the four nonspeech items in Table 1)	Phonological enhancement of ERPs for native phonemes
(d) Lexical memory trace activation for native words	Average of the three real-word stems versus the acoustically matched pseudoword stem	Lexical enhancement of ERPs for native words
(e) Processing of word meaning	Topographical distribution of an action verb versus that of a concrete noun	Difference in activation topographies (more frontal for action versus more posterior for visual words)
(f) (Morpho)syntactic processing	Syntactic versus asyntactic forms ending with [-t] (*gide*t vs. **midet*) and with [-n] (**giden* vs. *miden*)	ELAN/sMMN-like response

an alpha of 0.05; conditions with multiple tests (i.e., P1 and N1) as well as post hoc comparisons of ANOVA interactions were Bonferrroni corrected for multiple comparisons.

For graphic display and because most of the target components had frontocentral distributions, all waveforms are reported at the typical midline electrode location at Cz (except for the lexical semantics contrasts, which are reported at Fz and Pz); all ERPs were time-locked relative to sound onsets.

3 | RESULTS

3.1 | Obligatory auditory responses

Obligatory auditory responses were assessed in the nonspeech stimuli only in order not to confound them with any linguistic processes that may be reflected in ERPs at the same or overlapping latency range. We identified two early peaks in the GFP of the average of all four stimuli: at 78 ms and at 133 ms after sound onset. In order to optimize SNR as well as not test on identical data to those used for the temporal localization, we focused our statistical analyses on only one nonspeech stimulus, which was the musical rain based on the speech stimulus with the shortest consonant and thus the earliest vowel onset, namely, *bidt*. For the musical rain version of *bidt*, the two identified responses showed a positive frontocentral and a negative central distribution, respectively (Figure 4a), strongly indicating the P1-N1 complex (or P50 and N100, respectively). These two successive peaks were significantly different from zero (P1: $t(1,17) = 3.23$, $p = .01$, Hedges's $g_{av} = 0.72$; and N1: $t(1,17) = -2.74$, $p = .028$, Hedges's $g_{av} = -0.62$, Bonferroni corrected) when calculated as an average of our frontocentral electrode selection for the 20-ms time windows around the peaks. Mean P1 amplitude was + 0.45 μV ($SD = 0.59$), while N1 was on average -0.48 μV ($SD = 0.74$). This biphasic response was evident for all of the different stimuli in this passive listening setup, despite the simultaneous presentation of visual stimulation.

3.2 | Auditory attention allocation

Here, we contrasted the less-frequent, unusual, and highly salient nonspeech sounds (musical rain) against their acoustically matched speech counterparts (i.e., [bit], [git], [mit], [nit]). In the GFP of the average of the two conditions, we identified a salient peak at 220 ms resembling the timing of a P3a effect. The resulting 210–230 ms time window exhibited a significant difference between the two sets of responses, $t(1,17) = 14.02$, $p < .001$, Hedges's $g_{av} = 3.48$ (Figure 4b) with opposite polarities and with central distributions where the response to the nonspeech sounds was more positive than that to the speech sounds ($\Delta M = 1.91$ μV, $SD = 0.58$).

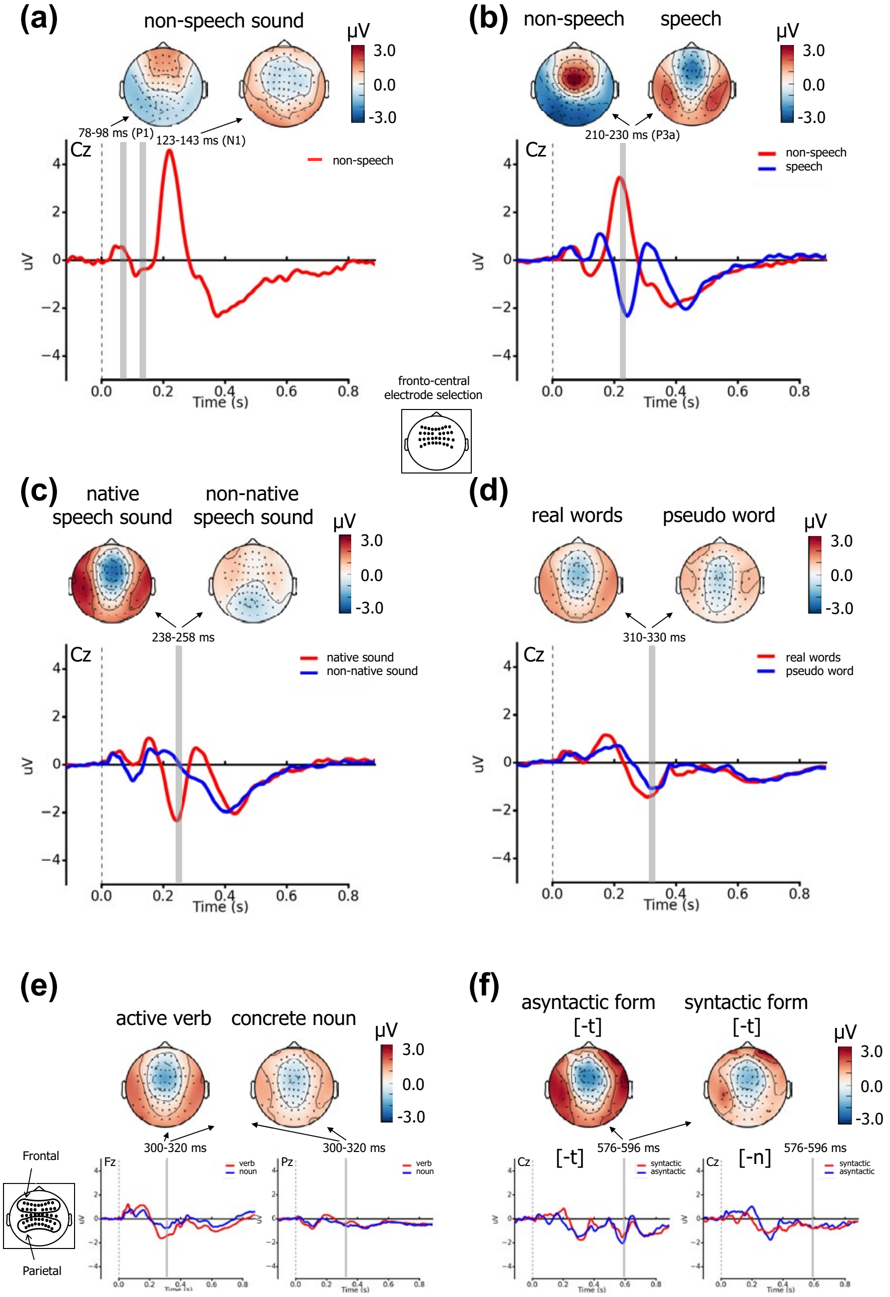

FIGURE 4 Waveforms of group-averaged ($n = 18$) ERPs and window-mean scalp topographies for each experimental contrast. (a) Obligatory auditory responses to the nonspeech sound based on [*bit*] (P1-N1 complex). (b) Automatic attention shift response (P3a) elicited by nonspeech sounds compared with matched speech sounds. (c) Phonological enhancement elicited by native phonology. (d) Lexical enhancement elicited by real words versus pseudoword. (e) Topographical differences elicited by lexicosemantic differences (more frontal distribution for action verb and more posterior distribution for concrete noun; waveforms displayed at Fz and Pz, respectively). (f) No significant differences between asyntactic and syntactic forms

3.3 | Phonetic and phonological processing

In the contrast comparing native versus nonnative phonemes (Figure 4c), we identified a centrally distributed peak at 248 ms after stimulus onset in the GFP of the average between the two conditions. The paired *t* test comparing responses in the two conditions in the associated time window of 238–258 ms showed a significant difference, $t(1,17) = -13.79$, $p < .001$, Hedges's $g_{av} = -1.98$, indicating a stronger and more negative response to the native sounds than to the nonnative sounds in this time window of interest ($\Delta M = -0.98\,\mu\text{V}$, $SD = 0.32$).

3.4 | Lexicality: Real versus pseudowords

In this contrast between real Danish words (*bide, gide, mide*) and a meaningless pseudoword (*nide*), all using native Danish phonology and phonotactics, we identified a peak in the GFP of the combined average of real words and the pseudoword in the range of lexical enhancement at 320 ms after sound onset. In the associated time window (310–330 ms), we found a significant enhancement, $t(1,17) = -5.88$, $p < .001$, Hedges's $g_{av} = -0.89$, for real words over the pseudoword, with the real words eliciting a more negative response than the pseudoword ($\Delta M = -0.31$, $SD = 0.22$; Figure 4d).

3.5 | Lexical semantics

Here, we compared topographical responses elicited by an action verb (*bide*, to bite) with those elicited by a concrete noun (*mide*, a mite). In the GFP of the average of the two conditions, we identified a salient peak already at 310 ms (Figure 4e) after stimulus onset, when identification of the word stem and thus lexical access were already possible, since the closest competitors (i.e., the irregular forms *bidt* and *mit*) differed from these forms from 106 ms and onward (cf. 2.2. Stimuli and Figure 1). The repeated measures ANOVA with condition (verb vs. noun) and anteriority (frontal vs. parietal) revealed a main effect of condition, $F(1, 17) = 44.78$, $p < .001$, $\eta^2_{\text{p}} = .72$, with the action verb generally eliciting a stronger negative response than the concrete noun, $t(1,17) = -6.69$, $p < .001$, Hedges's $g_{av} = -0.90$, as well as a main effect of anteriority, $F(1, 17) = 5.04$, $p < .001$, $\eta^2_{\text{p}} = .23$, with a generally stronger negative response at the frontocentral electrodes than at the parietal ones, $t(1,17) = -2.25$, $p = .038$, Hedges's $g_{av} = -0.86$. However, these main effects should be interpreted in the light of a significant interaction effect of condition and anteriority, $F(1, 7) = 15.46$, $p = .001$, $\eta^2_{\text{p}} = .48$, where the action verb elicited a stronger negative response than the concrete noun at frontocentral electrodes, $t(1,17) = -5.43$, $p < .001$, Hedges's $g_{av} = -0.70$, as revealed by Bonferroni-corrected post hoc pairwise comparisons.

3.6 | Morphosyntax

Here, we compared the morphemes expressing regular past participle and definiteness in Danish for the pair of stems where this resulted in a cross-over design, that is, **midet* versus *gidet* ([have] bothered) and **giden* versus *miden* (the mite). We identified the peak for this comparison within the 576–596 ms window, corresponding to ~170 ms after the onset of the syntactic morphemes [-t] and [-n]. This identification was based on the [-t] condition as there were no discernible peaks in the [-n] condition. We found no statistically significant differences in either contrast when comparing responses between the grammatical and the ungrammatical conditions (all $ps > .05$), although visual investigation suggested stronger negativity for the asyntactic form, as expected.

Finally, none of our a priori contrasts predicted latency shifts or laterality effects, with the main focus being on absolute amplitude differences (apart from the semantic contrast where topographic effects were expected—and found—in the rostrocaudal dimension). Visual inspection of the ERPs and topographies indeed confirmed that no such shifts or effects were observed in the data. Ad hoc ANOVAs with a factor laterality using a larger array of electrodes did not show any laterality effects either (note the predominantly central distribution of responses in Figure 4, typical of auditory ERPs).

4 | DISCUSSION

We present an EEG paradigm aimed at assessing several speech-related processes in the absence of focused attention on the auditory stimuli. Based on the established time course of several ERP components, we adopted the multifeature paradigm and combined a range of stimulus manipulations (involving both speech and nonspeech properties) in a passive listening design. This led to a set of results, which we will discuss below.

4.1 | Basic auditory processing

The different types of auditory stimuli used in this study elicited an initial ascending curve systematically followed by a negative-going one. The nonspeech condition, which we chose to focus on here (as unconfounded by any linguistic processes), elicited both the positive peak at 78 ms and the negative one at 133 ms after the sound onset, with the maximum amplitude at frontocentral electrodes. These two successive deflections have been reported as the P50 and N100, respectively, or the P1-N1 complex (Näätänen & Picton, 1987). These components of the auditory evoked potentials are known to occur with latencies between 40 and 90 ms after sound onset for the P50 (Kurthen et al., 2007) and between 70 and 140 ms for the N100 response (Picton et al., 1999), which matches the latencies observed here. Being obligatory auditory responses to sound onsets, the P50 and the N100 can be elicited by any type of auditory stimulus and are understood to reflect different stages of auditory processing. The N100 is understood as indexing detection of auditory events by the brain (Näätänen & Picton, 1987) and tracking the perceptual features of auditory stimuli (Hillyard & Picton, 1978), while the P50 is said to reflect sensory gating (Adler et al., 1982), both being common steps in processing nonspeech sounds and spoken language alike. In sum, these two components are well-established indexes of the generally normal functioning of the auditory system (Korzyukov et al., 2007; Ostroff, Martin, & Boothroyd, 1998; Sharma et al., 2005; Vaughan & Ritter, 1970; Wagner et al., 2017).

4.2 | Auditory attention allocation

To test automatic shifts of auditory attention, we used four infrequent nonspeech musical rain sounds (in total accounting for only 10% of the sounds, all remaining stimuli being speech). Musical rain shares its basic acoustic properties with the speech it was based on but does not resemble any human articulation. These rare and unusual nonspeech deviants elicited a positivity peaking within 210–230 ms with a central distribution (see Figure 4b) while responses to the corresponding speech condition showed the opposite pattern with a negative-going deflection. With the vast majority (90%) of all sounds being speech, such unusual rare sounds could have caused an automatic shift of auditory attention to the novel deviant input, reminiscent of a P3a (or novelty P3) component, previously found to be elicited by novel nonspeech stimuli in a repetitive sound sequence. In oddball paradigms, the P3a is elicited by rare, novel, or salient stimuli and is understood to mark an involuntary shift of attention (and is thus considered "preattentive"; Light, Swerdlow, & Braff, 2007; Schwartze, Rothermich, Schmidt-Kassow, & Kotz, 2011) toward unusual, unexpected, and/or distracting stimuli, reflecting automatic attentional processes associated with response orientation (Friedman et al., 2001; Knight, 1984). It typically has a central/frontocentral distribution (Escera, Alho, Winkler, & Näätänen, 1998; Escera & Corral, 2007) with latencies varying between 175–350 ms (Bell, Dentale, Buchner, & Mayr, 2010; Bouwer, Werner, Knetemann, & Honing, 2016; Escera et al., 1998; Escera & Corral, 2007; Picton et al., 1999; Roth, 1973; Yago, Corral, & Escera, 2001).

Since our participants were asked to focus on a silent film and ignore the auditory input, it is highly plausible that the rarely occurring, deviant nonspeech sounds acted as distractors, causing participants to involuntarily shift their attention toward the auditory input, thus yielding a P3a. This response therefore appears to reflect normal functioning of the attention-orienting system, and may thus also serve as a task-invariant index of auditory processing.

4.3 | Phonetic/phonological processing

To test the applicability of our paradigm for assessing the phonological level of auditory/linguistic processes, we compared responses between two types of otherwise acoustically matched stimuli. Though it was not possible to use two sounds that were fully physically controlled—since they had to be different sounds—we matched them for their overall physical/acoustic properties and the overall phonetic makeup. The two types each contained a different vowel sound: (a) a sound ([i]), which is part of the Danish phonological system, and (b) a nonnative sound (nasal [ɔ̃]) unfamiliar to native speakers of Danish. We found an enhanced response to the phonological native stimulus with a peak at 248 ms (i.e., ~60 ms after the onset of the critical phonemes). Since the stimuli were matched for loudness, spectral characteristics, and envelope, the significant difference between these two conditions was likely driven not purely by acoustic effects but also by phonological processing. For instance, in a study using a passive oddball paradigm, contrasting responses to native and nonnative phonology, Näätänen and colleagues (1997) reported an enhancement of the MMN responses to native over nonnative phonemes (vowels) in the latency range of 150–240 ms. They argued that the enhancement was triggered by the activation of language-specific memory traces for phonemic items. Furthermore, Peltola and colleagues (2003) addressed phoneme discrimination in native and nonnative speakers and also reported a larger response to native phonemes over nonnative/nonphonotactic stimuli, taken to reflect memory traces for native phonology, not present for the nonnative items. A more recent study by Kimppa and colleagues (2015) consisting of a passive equiprobable paradigm comparing responses to nativelike pseudowords to nonnative novel words also reported a stronger activation to items containing native phonology. This was found at 50 ms after the stimulus identification point similar to the latency observed here. The same interpretation as above could also hold for the present results. Since we used a sound that does not exist in Danish, it is likely that it matches no existing phonological memory trace. This would explain the absence of the negative deflection for nonnative phonology otherwise found for the stimuli with native phonology, making this ERP effect a potential index of the automatic access of the native phonology.

4.4 | Lexical memory trace activation

In this comparison, we explored the possible differences between responses to real words and meaningless pseudowords. We found a significant effect with a peak at ~320 ms where real words showed an enhanced negative potential. Given that the stimuli used in this comparison were maximally matched acoustically and obeyed the rules of Danish phonology and phonotactics, these response differences are best explained in terms of words' lexical status. Signs of lexical processing around the 300 ms poststimulus have been previously described in attended settings (Embick et al., 2001; see review by Pylkkänen & Marantz, 2003), in association with the early automatic lexical access occurring in the recognition stage of a word (Pylkkänen et al., 2002; Pylkkänen & Marantz, 2003). Our results are in line with these findings as the response indexing the difference between real and pseudowords occurred at ~300 ms after word onset. The above studies, however, used active attention-demanding tasks and reported larger responses for pseudowords over real words, while we find here an enhanced response generated by real words of Danish in an unattended setting. This inversion is in line with previous research suggesting that in unattended settings the response is dominated by the lexical access of real preexisting memory traces, while attention allocation allows active parsing and analysis of unfamiliar items, which, being more effortful, leads to stronger pseudoword responses (Garagnani, Wennekers, & Pulvermüller, 2008; Garagnani et al., 2009; Shtyrov et al., 2009). In this sense, our results are more compatible with the line of research on automatic memory trace activation where lexicality effects are seen between as early as 30–50 ms and as late as 150–200 ms after disambiguation/word recognition point; these have been observed in the MMN in traditional oddball and multifeature designs as well as in nonoddball passive sequences (MacGregor et al., 2012, Shtyrov et al., 2009, Shtyrov & Lenzen, 2017). These studies suggest that strong lexical representations for real words are underpinned by interconnected memory circuits that can be activated even in the absence of attention on the input. In contrast, the pseudoword form matches no representation in the lexicon and thus cannot lead to a strong activation in the absence of attention. Considering that the current items may be fully identified only at the boundary between the two syllables, which commences at 280 ms, our latency corresponds to earlier findings.

4.5 | Lexical semantics

We also investigated the sensitivity of our paradigm to semantic processing, using two words closely matched acoustically but differing in their meaning, as one was an action verb (*bide*, to bite) and the other one a noun designating an animal (*mide*, a mite). Both conditions showed an enhanced negativity, but with different topographical distributions in the 300–320 ms time window. This was manifest as a Condition × Topography interaction, indicating that the processing of the action verb gave rise to a more frontal distribution of the ERP, whereas a more posterior distribution was found for the concrete noun. The finding is generally in line with, for instance, a study by Damasio and Tranel (1993) who showed that the brain areas involved in verb processing were more frontal, while concrete nouns involved the more posterior cortical areas linked with visual processing. Also in line with the present topographical differences, a large number of studies investigating the role of the motor cortex in language comprehension have reported activation in the motor areas when processing action-related words (both verbs and nouns; see, e.g., Hauk et al., 2004; Shtyrov et al., 2004b; Shtyrov, Butorina, Nikolaeva, & Stroganova, 2014; notably, the latter two results were obtained using MMN responses produced in nonattend settings, similar to those used here). In fact, even the verb-noun topographical distinction found in some studies has been claimed to be merely a side effect of verbs being more often action related than nouns, rather than a lexical class effect per se (Moseley & Pulvermüller, 2014). The difference in our topography patterns may thus indicate the retrieval of the word features at the lexical semantics level (i.e., the motor aspect of the action verb). While we cannot ascertain whether the difference between the two distributions is linked to the semantics or the word class per se (or both), the crucial outcome is that such a high-level linguistic contrast leads to detectable ERP differences in our passive paradigm, supporting its potential applicability for testing lexical-semantic processing.

4.6 | Morphosyntactic processing

Lastly, we aimed at comparing responses between morphosyntactically correct and incorrect complex words. Previous research with similar (but not identical) morphosyntactic violations, such as English past tense or Finnish inflections in passive oddball settings, did find an automatically enhanced ELAN-like response for them (Bakker, Macgregor, Pulvermüller, & Shtyrov, 2013; Leminen et al., 2013; Pulvermüller et al., 2008; Shtyrov et al., 2003). This response can be classified as ELAN or syntactic MMN, elicited in similar designs by agreement violations, which is interpreted as an index of automatic combinatorial processing in the brain effective at both phrase (syntax) and word (morphosyntax) levels (Bakker et al., 2013; Cappelle, Shtyrov, & Pulvermüller, 2010; Leminen et al., 2016; MacGregor & Shtyrov, 2013). Although visual inspection suggested stronger negativity for the asyntactic form at ∼170 ms after the onset of the stimulus-final syntactic morphemes, as predicted, we found no significant differences in either contrast (all $ps > .05$). This lack of statistically significant effects here can be explained by various factors. This was the first attempt to do this in Danish, and we used a specific feature of Scandinavian languages where determiners, similar to suffixes, can be attached poststem and depend on gender agreement (e.g., hus**et—the** house, but kvind**en—the** woman). Furthermore, they are partly homophonous with other inflectional forms (gå**et—**[have] walk**ed**), which creates a unique possibility for controlled morphosyntactic manipulations. However, this particular type of violation in Danish has not been tested before, and more investigations are needed to address poststem determiner parsing. Furthermore, here we used forms that were intentionally overarticulated for clarity, superfluously clearly pronouncing the word-final consonants marking determiner/past participle. Although such overarticulated pronunciation can be used when words are uttered in isolation (e.g., in a language lesson), this is not a typical form used in standard Danish. In real-life connected speech, especially when it concerns inflected forms, Danish is in fact characterized by a high degree of reduction (Hilton, Schüppert, & Gooskens, 2011; Schüppert, Hilton, Gooskens, & Van Heuven, 2012), and affixes are not fully articulated. This means that our stimuli may not have been perceived as normal native words and thus failed to generate the predicted ELAN-like effects.

Another possible reason could be attributed to the ELAN component per se. Previous research has indicated that it is particularly difficult to replicate (Steinhauer & Drury, 2012), and this could be something we have encountered here as well, particularly given the phonological issue above. ELAN has only been found for some types of syntactic violations, and has not been tested for the kind of Danish agreements used here. Moreover, whereas ELAN-like syntactic MMNs were found in passive oddball designs for different languages, some studies have not been able to replicate this phenomenon either (Brunelliere, Franck, Ludwig, & Frauenfelder, 2007). Future studies, which will be able to investigate syntax processing in Danish in more depth using phonologically controlled stimuli with a variety of syntax features, are therefore required to address this lack of a clear effect.

4.7 | Limitations and future directions

In this study, we aimed to test the validity of a task-free auditory stimulation paradigm assessing several incremental levels of the brain's language processing, ranging from basic acoustic processes to lexical semantics to morphosyntax. While we have shown that a variety of features can indeed be assessed in such a multifeature passive listening paradigm, we should also treat this initial test with caution and need to mention a few limitations pertinent to the current investigation.

First, as already mentioned, the syntactic contrast should be explored further in future studies in order to find a reliable protocol that can be implemented in an attention- and task-free fashion to probe this level of processing. This may be addressed in future studies by employing more salient features (e.g., using simple phrases), as well as making their articulation more natural.

Second, and important, to make such a paradigm usable for objective assessment of language in clinical populations or unresponsive participant groups, further steps are required. Future research needs to assess the protocol's reliability on a single-subject level, which will require optimization in terms of the saliency of the contrasts involved, the number of trials obtained, and the use of different statistical tools. One other possibility is to use a method with a higher SNR such as magnetoencephalogram (MEG), a patient-friendly and safe noninvasive neuroimaging method capable of registering magnetic counterparts of the same ERP components. Crucially, the paradigm should be tested for its applicability in individuals with neurocognitive deficits, such as disorders of consciousness (DOCs, e.g., coma). This could both validate its usability in clinical groups and potentially find other biomarkers (such as any specific latency delays, which were not found in this healthy-subject study). Oddball auditory paradigms have been applied to DOCs and even used to predict coma recovery based on the MMN amplitude (Fischer, Dailler, & Morlet, 2008; Fischer & Luauté, 2005; Fischer, Luauté, Adeleine, & Morlet, 2004; Fischer, Luauté, & Morlet, 2010; Fischer, Morlet, & Giard, 2000), but so far none of the previous studies included such a comprehensive range of contrasts as suggested here.

Finally, we focused on quantitative effects, looking for absolute amplitude differences between conditions. Any potential application of this design would benefit from a simple protocol that could use a handful of sensors with a straightforward comparison between conditions. Indeed, most observed effects had a frontocentral distribution typical of auditory responses, suggesting that these sites may be optimal for any future applications. Whereas we did run a more complex ANOVA with topographic factors, we did not find any statistically topographic effects (such as laterality) except where they were predicted (i.e., for the semantic contrast). However, in order to understand better the underlying neuroanatomical sources of the effects at hand, a more fine-grained approach is needed with better spatial resolution. One direction for this could be to use MEG with single-subject MR images and source estimation techniques that could pinpoint cortical generators of the observed activity with more certainty.

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