Linguistic processing of task-irrelevant speech at a Cocktail Party

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Abstract

Paying attention to one speaker in noisy environments can be extremely difficult. This is because task-irrelevant speech competes for processing resources with attended speech. However, whether this competition is restricted to acoustic-phonetic interference, or if it extends to competition for linguistic processing as well, remains highly debated. To address this debate, here we test whether task-irrelevant speech sounds are integrated over time to form hierarchical representations of lexical and syntactic structures.

Neural activity was recorded using Magnetoencephalography (MEG) during a dichotic listening task, where human participants attended to natural speech presented to one ear, and task-irrelevant stimuli were presented to the other. Task-irrelevant stimuli consisted either of random sequences of syllables (Non-Structured), or syllables ordered to form coherent sentences (Structured). Using hierarchical frequency-tagging, the neural signature of different linguistic-hierarchies within the Structured stimuli - namely words, phrases and sentences – can be uniquely discerned from the neural response.

We find that, indeed, the phrasal structure of task-irrelevant stimuli was represented in the neural response, primarily in left inferior frontal and posterior parietal regions. Moreover, neural tracking of attended speech in left inferior frontal regions was enhanced when task-irrelevant stimuli were linguistically structured. This pattern suggests that syntactic structure-building processes are applied to task-irrelevant speech, at least under these circumstances, and that selective attention does not fully eliminate linguistic processing of task-irrelevant speech. Rather, the inherent competition for linguistic processing resources between the two streams likely results in the increased listening effort experienced when trying to focus selective attention in multi-speaker contexts.

Significance statement

This study addresses the fundamental question of how the brain deals with competing speech in noisy environments. Specifically, we ask: when one attempts to focus their attention on a particular speaker, what level of linguistic processing is applied to other, task-irrelevant speech? By measuring neural activity, we find evidence that the phrasal structure of **task-irrelevant speech** is indeed discerned, indicating that linguistic information is integrated over time and undergoes some syntactic analysis. Moreover, neural responses to **attended speech** were also enhanced in speech-processing regions, when presented together with comprehensible yet task-irrelevant speech. These results nicely demonstrate the inherent competition for linguistic processing resources among concurrent speech, providing evidence that selective attention does not fully eliminate linguistic processing of task-irrelevant speech.

Introduction

The seminal speech-shadowing experiments conducted in the 50s and 60s set the stage for studying one of the primary cognitive challenges encountered in daily life: how do our perceptual and linguistic systems deal effectively with competing speech inputs? [1–3]. Over the past decades, a wealth of behavioral and neural evidence has accumulated showing that when only one speech-stream is behaviorally relevant, auditory and linguistic resources are devoted to its preferential encoding at the expense of other task-irrelevant input. Consequentially, this so-called 'attended' message can be shadowed, comprehended, and remembered, whereas very little of competing task-irrelevant speech is explicitly recalled [4–8]. This attentional selection is accompanied by attenuation of speech-tracking for unattended speech in auditory region [9–14] as well as language-related regions [15], particularly for linguistic-features of the speech [16–19]. However, as demonstrated even in the earliest studies, the content of task-irrelevant speech is probably not fully suppressed and can affect listener behavior in a variety of ways [20–22]. Indeed, despite decades of research, the extent to which concurrent speech are processed and the nature of the competition for resources between 'attended' and 'task-irrelevant' input in multi-speaker contexts is still highly debated [23–26].

Fueling this debate are often-conflicting empirical findings regarding whether or not task-irrelevant speech is processed for semantic and linguistic content. Many studies fail to find behavioral or neural evidence for processing task-irrelevant speech beyond its acoustic features [16,25,27]. However, others are able to demonstrate that at least some linguistic information is gleaned from task-irrelevant speech. For example, task-irrelevant speech is more distracting than non-speech or incomprehensible distractors [28–35], and there are also indications for implicit processing of the semantic content of task-irrelevant speech, manifest through priming effects or memory intrusions [35–41]. Known as the 'Irrelevant Sound Effect' (ISE), these are not always accompanied by explicit recall or recognition [42–44], although in some cases task-irrelevant words, such as one's own name, may also 'break in consciousness' [1,2,45,46].

Behavioral findings indicating linguistic processing of task-irrelevant speech have been interpreted in two opposing ways. Proponents of Late-Selection attention theories understand them as reflecting the system's capability to apply linguistic processing to more than one speech stream in parallel, albeit mostly pre-consciously [47–50]. However, others maintain an Early-Selection perspective, namely, that only one speech stream can be processed linguistically due to inherent processing bottlenecks, but that listeners may shift their attention between concurrent streams giving rise to occasional (conscious or pre-conscious) intrusions from task-irrelevant speech [51–53].

Adjudicating between these two explanations experimentally is difficult, due to the largely indirect-nature of the operationalizations used to assess linguistic processing of task-irrelevant speech. Moreover, much of the empirical evidence fueling this debate focuses on detection of individual 'task-irrelevant' words, effects that can be easily explained either by parallel processing or by attention-shifts, due to their short duration.

In attempt to broaden this conversation, here we use objective neural measures to evaluate the level of processing applied to task-irrelevant speech. Using a previously establish technique of hierarchical frequency-tagging [54,55], we are able to go beyond the question of detecting individual words and probe whether linguistics processes that require integration over longer periods of time – such as syntactic structure building – are applied to task-irrelevant speech. To study this, we recorded brain activity using magnetoencephalography (MEG) during a dichotic listening selective-attention experiment. Participants attended to narratives of natural speech presented to one ear, while instructed to ignore speech input from the other ear (Figure 1). Task-irrelevant stimuli consisted of sequences of syllables, presented at a constant rate (4H), with their order manipulated to either create linguistically Structured or Non-Structured sequences. Specifically, for the Non-Structured stimuli syllables were presented in a completely random order, whereas in the Structured stimuli syllables are ordered to form coherent words, phrases and sentences. In keeping with the frequency-tagging approach, each of these linguistic levels is associated with a different frequency (words - 2Hz, phrases - 1Hz, sentences - 0.5Hz). By structuring task-irrelevant speech in this way, the two conditions were perfectly controlled for low-level acoustic attributes that contribute to energetic masking (e.g. loudness, pitch, and fine-structure), as well as for the presence of recognizable acoustic-phonetic units, which proposedly contributes to phonetic interference during speech-on-speech masking [28,34,56]. Rather, the only difference between the conditions was in the order of the syllables which either did or did not form linguistic structures. Consequentially, if the neural signal shows peaks at frequencies associated with linguistic-features of Structured task-irrelevant speech, as has been reported previously when these type of stimuli are attended [16,54,55], this would provide evidence that integration-based processes operating on longer time-scales are applied to task-irrelevant speech, for identifying longer linguistic units comprised of several syllables. In addition, we also tested whether the neural encoding of the attended speech itself was affected by the linguistic structure of task-irrelevant speech, which could highlight the source of potential tradeoffs or competition for resources when presented with competing speech [10,11,14,15].

Results

Data from one participant was excluded from all analyses due to technical problems during MEG recording. Six additional participants were removed only from source estimation analysis due to technical issues.

Behavioral results

Behavioral results reflecting participants responses on comprehension questions about attended narratives were significantly above chance [M=0.715, SD=±0.15; t(28)=26.67, p<0.001]. There were no significant differences in behavior as a function of whether task-irrelevant speech was Structured or Non-Structured conditions [t(28)=-0.31, p=0.75].

Hierarchical frequency-tagged responses to task-irrelevant speech

Scalp-level spectra of the Inter-trial phase coherence (ITPC) showed a prominent peak at the syllabic rate (4Hz) in response to both Structured and Non-Structured hierarchical frequency-tagged speech, with a 4-pole scalp-distribution common to MEG recorded auditory responses (Figure 2a). As expected, there was no significant difference between Structured and Non-Structured condition in the 4Hz response (p=0.899). Importantly, we also observed a peak at 1Hz in the Structured condition, which was significantly stronger than in the Non-Structured condition (p=0.045). The scalp-distribution of the 1Hz peak did not conform to the typical auditory response topography, suggesting different neural generators. No observable peaks were evident at 2Hz or 0.5Hz nor did the responses at these frequencies differ between conditions.

In order to determine the neural source of the 1Hz peak in the Structured condition, we repeated the spectral analysis in source space. An inverse solution was applied to individual trials and the ITPC was calculated in each voxel. As shown in Figure 2b, the source-level ITPC spectra, averaged over each hemisphere separately, is qualitatively similar to that observed at the scalp-level with clear peaks at 4Hz in both conditions and at 1Hz in the Structured condition only. Statistical comparison of the 1Hz peak between conditions revealed a significant difference between the Structured and Non-Structured condition over the left hemisphere (p=0.026), but not over the right hemisphere (p=0.278).

Figure 2c shows the source-level distribution within the left hemisphere of the difference in 1Hz ITPC between the Structured and Non-Structured condition. The effect was observed primarily in frontal and parietal regions. Statistical testing evaluating the difference between conditions was performed in 22 pre-determined ROIs per hemisphere, using a permutation test. This indicated significant effects in several ROIs in the left hemisphere including the inferior-

frontal cortex and superior parietal cortex, as well as the mid-cingulate and portions of the middle and superior occipital gyrus (cluster-corrected p=0.002). No ROIs survived multiple-comparison correction in the right hemisphere (cluster- corrected p=0.132), although some ROIs in the right cingulate were significant at an uncorrected level (p<0.05).

With regard to the 4Hz peak, it was localized as expected to bilateral auditory cortex and did not differ significantly across conditions in either hemisphere (left hemisphere: p=0.155, right hemisphere: p=0.346). We therefore did not conduct a more fine-grained analysis of different ROIs. As in the scalp-level data, no peaks were observed at 2Hz and no significant difference between conditions (left hemisphere: p=0.963, right hemisphere: p=0.755).

Speech Tracking of attended speech

Speech tracking analysis of responses to the attended narrative yielded robust TRFs (scalp level predictive power r=0.1, p<0.01 vs. permutations). The TRF time-course featured two main peaks, one ~80ms and the other ~140ms, in line with previous TRF estimations [14,57,58]. Both the scalp-level and source-level TRF analysis indicated that TRFs were predominantly auditory – showing the common 4-pole distribution at the scalp level (Figure 3a) and localized primarily to auditory cortex in the source-level analysis (Figure 3b; 140ms).

When comparing the TRFs to attended speech as a function of whether the competing task-irrelevant stimulus was Structured vs. Non-Structured, some interesting differences emerged. Spatial-temporal clustering permutation test on the scalp-level TRFs revealed significant differences between the conditions between 70-180 ms (p<0.05; cluster corrected), including both the early and late TRF peaks, at a large number of sensors primarily on the left (Figure 3a&c). Specifically, TRF responses to attended speech were enhanced when the task-irrelevant stimulus was Structured condition vs. Non-Structured. The effect was observed at the scalp level with opposite polarity in frontal vs. medial sensors, and was localized at the source level to a single cluster in the left inferior-frontal cortex, that included portions of the insula and orbito-frontal cortex (Fig 3d; spatial-temporal clustering p=0.0058).

Discussion

In this MEG study, frequency-tagged hierarchical speech was used to probe the degree to which linguistic processing is applied to task-irrelevant speech, and how this interacts with processing attended speech. As expected, we observe obligatory acoustic representation of task-irrelevant speech, regardless of whether it was Structured or Non-Structured, which manifest as a 4Hz syllable-level response localized to bilateral auditory regions in the STG/STS. Critically, for Structured task-irrelevant speech we also find evidence for neural tracking of the phrasal structure, with a 1Hz peak localized primarily to left inferior-frontal cortex and left posterior-parietal cortex. The regions are not associated with low-level processing, but rather play an important role in speech processing and higher order executive functions [59–64]. Additionally, we find that the speech-tracking response to *attended* speech in left inferior frontal cortex was also affected by whether task-irrelevant speech was linguistically Structured or not. These results contribute to ongoing debates regarding the nature of the competition for processing resources during speech-on-speech masking, demonstrate that linguistic processes requiring integration of input over relatively long timescales can indeed be applied to task-irrelevant speech.

The debate surrounding linguistic processing of task-irrelevant speech

Top-down attention is an extremely effective process, by which the perceptual and neural representation of task-relevant speech are enhanced at the expense of task-irrelevant stimuli, and speech in particular [10,11,13–15]. However, the question still stands: what degree of linguistic processing is applied to task-irrelevant speech? One prominent position is that attention is required for linguistic processing and therefore speech that is outside the focus of attention is not processed beyond its sensory attributes [25]. However, several lines of evidence suggest that linguistic features of task-irrelevant speech can be processed as well, at least under certain circumstances. For example, task-irrelevant speech is more disruptive to task performance if it is intelligible, as compared to unintelligible noise-vocoded or rotated speech [29–31,33,34,65] or a foreign language [28,66–69]. This effect, referred to as informational masking, is often attributed to the detection of familiar acoustic-phonetic features in task-irrelevant speech, that can lead to competition for phonological processing ('phonological interference') [56,70–73]. However, the phenomenon of informational masking alone is insufficient for determining the extent to which task-irrelevant speech is processed beyond identification of phonological units.

Other lines of investigation have focused more directly on whether task-irrelevant speech is represented at the semantic level. Findings that individual words from a task-irrelevant source

are occasionally detected and recalled, such as one's own name, [1,44–46,74], have been taken as evidence that task-irrelevant inputs can be semantically processed, albeit the information may not be consciously available. Along similar lines, a wealth of studies demonstrate the 'Irrelevant Sound Effect' (ISE), showing that the semantic content of task-irrelevant input affects performance on a main task, mainly through priming effects and interference with short-term memory [37,38,77,39–43,50,75,76]. However, an important caveat precludes interpreting these findings as clear-cut evidence for semantic processing of task-irrelevant speech: Since these studies primarily involve presentation of arbitrary lists of words (mostly nouns), usually at a relatively slow rate, an alternative explanation is that the ISE is simply a result of occasional shifts of attention towards task-irrelevant stimuli [25,78]. Similarly, the effects of informational masking discussed above can also be attributed to a similar notion of perceptual glimpsing, i.e., gleaning bits of the task-irrelevant speech in the short 'gaps' in attended speech [34,51,53]. These claims – that effects of task-irrelevant speech are not due to parallel processing but reflect shifts of attention - are extremely difficult to reject empirically, as they would require insight into the listeners' internal state of attention, which at present is not easy to operationalize.

Phrase-level response to task-irrelevant speech

In attempt to broach the larger question of processing task-irrelevant speech, the current study takes a different approach by focusing not on detection of single words, but on linguistic processes that operate over longer timescales. To this end we used continuous speech rather than word-lists, as both the attended and task-irrelevant stimuli, whose processing requires accumulating and integrating information over time, which is strikingly different than the point-process nature of listening to word-lists [79]. Using continuous speech is also more representative of the type of stimuli encountered naturally in the real world [80–83]. In addition, by employing hierarchical frequency tagging, we were able to obtain objective and direct indications of which levels of information were detected within task-irrelevant speech. Indeed, using this approach we were able to identify a phrase-level response for Structured task-irrelevant speech, which serves as an indication that these stimuli are indeed processed in a manner sufficient for identifying the boundaries of syntactic structures.

An important question to ask is whether the phrase-level response observed for task-irrelevant speech can be explained by attention shifts? Admittedly, in the current design participants could shift their attention between streams in an uncontrolled fashion. However, in order to observe a reliable peak in the neural response at any of the linguistic-frequencies for Structured task-irrelevant speech, such shifting would: (a) either have to occur on a regular basis,

which would be an indication that underlying structure was indeed detected, or (b) if attention-shifts occur irregularly, the emergence of a phase-rate peak in the neural response would indicate that bits of 'glimpsed' information are integrated over a prolonged period of time. Either way, the resulting phrase-level response would indicate integration of phonetic-acoustic information over time, and the formation of long-scale linguistic representations for task-irrelevant speech, in parallel to processing the attended speaker.

The current study is similar in design to another recent study by Ding et al. [16] where Structured frequency-tagged speech was presented as a distractor. But, in contrasts to the results reported here, they found no evidence for peaks at any linguistic-related frequencies in the neural response to task-irrelevant speech. However, these two studies differ in one important way – in the listening effort that was required of participants in order to perform their task. While in the current experiment attended speech was presented at its natural rate, mimicking the type of listening effort encountered when processing speech in real-life, in the study by Ding et al. [16] attended speech was time-compressed by a factor of 2.5 and naturally occurring gaps were removed, making the comprehension task extremely effortful [84,85]. Comparison between these two studies invites re-framing of the question regarding the type / level of linguistic processing applied to task-irrelevant speech, a propels us to think about this issue not as a yes-or-no dichotomy, but perhaps as a more flexible process that depends on the specific context [58]. Along similar lines, Load Theory of Attention proposes that the allocation of processing resources among competing inputs can vary as a function of the perceptual traits and cognitive load imposed by the task [86,87]. Given the limited nature of processing resources, particularly for linguistic processing, it makes intuitive sense that if the main task imposes relatively low perceptual and cognitive load, then residual resources may be available to process task-irrelevant stimuli, but that this might not be the case as the task becomes more difficult [88–90]. This perspective offers a plausible explanation for the diverse results reported in the literature with regard to how task-irrelevant speech is processed specifically for the discrepancy between results of the current study and the study by Ding et al. [16]. Supporting this perspective, others have also observed that the level of processing applied to task-irrelevant stimuli can be affected by task demands [91,92]. Moreover, individual differences in attentional abilities, and particularly the ability to process concurrent speech, have been attributed partially to working memory capacity, a trait associated with the availability of more cognitive resources [39,93–95] but cf. [96].

To summarize, adopting the perspective that task-irrelevant speech is processed only at an acoustic but not at a linguistic level seems to be too extreme, as the current results and some previous findings provide positive examples to the contrary. Rather, they invite a more flexible account of the processing bottlenecks within the speech processing system, which takes into consideration the perceptual and cognitive load imposed by competing stimuli in a given context, in line with load theory of attention [88,90,97–99]. As observed here, this allows for some degree of parallel processing of concurrent speech, at least under conditions where these loads are not excessively high, but are similar to those encountered in real-life [93].

The brain regions where phase-level response is observed

The phrase-level neural response to task-irrelevant Structured speech was localized primarily to two left-lateralized clusters: one in the left anterior fronto-temporal cortex and the other in left posterior-parietal cortex. The fronto-temporal cluster, which included the IFG and insula, is known to play an important role in speech processing [59,60,100]. The left IFG and insula are particularly associated with linguistic processes that require integration over longer periods of time, such as syntactic structure building and semantic integration of meaning [79,101,102], and are also recruited when speech comprehension requires effort, such as for degraded or noise-vocoded speech [103–106]. Accordingly, observing a phase-level response to task-irrelevant speech in these regions is in line with their functional involvement in processing speech under adverse conditions.

With regard to the left posterior-parietal cluster, the interpretation for why a phrase-level response is observed there is less straightforward. Although some portions of the parietal cortex are involved in speech processing, these are typically more inferior than the cluster found here [107,108]. However, the posterior-parietal cortex does play an important role in both verbal and non-verbal working-memory [61,62,109–115]. Detecting the phrasal structure of task-irrelevant speech, while focusing primarily on processing the attended speech, likely requires substantial working memory for integrating chunks of information over time. Indeed, attention and working-memory are tightly linked constructs [111,116,117], and as mentioned above, the ability to control and maintain attention is often associated with individual working memory capacity [39,93–95,118]. Therefore, one possible interpretation for the presence of a phrase-level response to task-irrelevant speech in the left posterior-parietal cortex, is that it assists in forming and maintaining a representation of task-irrelevant stimuli in working memory, perhaps as a means for monitoring the environment for potentially important events [81].

Why no word-level response?

Although in the current study we found significant neural response to task-irrelevant speech at the phrasal-rate, we did not see peaks at the word- or at the sentence-rates. Regarding the sentence-level response, it is difficult to determine whether the lack of an observable peak indicates that the stimuli were not parsed into sentences, or if this null result is due to the technical difficulty of obtaining reliable peaks at low-frequencies (0.5 Hz) given the to the 1/f noise-structure of neurophysiological recordings [119,120]. Hence, this remains an open question for future studies. Regarding the lack of a word-level response at 2Hz for Structured task-irrelevant stimuli, it is important to first note that even if we ***had*** seen a 2 Hz peak in the neural response, this could not be reliably interpreted as reflecting parsing of individual words, due to the nature of the stimuli whose modulation spectrum also contained a 2Hz peak (see Method and Supplementary Materials). Since no such peak was observed here this alleviates possible methodological concerns, but also raises an important cognitive question: Since phrases are comprised of individual words, why is phase-level response generated without a word-level response? We offer some speculations as to why this might be the case. One possibility is simply that this is a null-result, and that the lack of an observable word-level peak does not necessary imply that words were not detected, but simply that the current method was not sufficiently sensitive to bring it out, or perhaps the linguistic word-response was cancelled out by phase-reversal relative to the acoustic 2Hz response [121]. However, another possibility is related to the proposed functional dissociation between lexical processes involved in word-identification, and syntactic structure-building processes [60,122]. Counter to the notion that individual lexemes are necessary 'building blocks' for syntactic structuring, lexical and syntactic processes are actually considered to be separable cognitive processes, that also rely on partially different neural substrates [102,123–125]. Indeed, as shown recently, syntactic phrasal structure can be identified even in the complete absence of lexical information [126], which further supports the possibility that phrasal boundaries can be detected irrespective of full lexical analysis. To summarize, the degree to which individual words are identified in task-irrelevant speech, and whether this is independent of phrase-level parsing, remains to be explored in future research.

Task-irrelevant influence on processing attended speech

Besides analyzing the frequency-tagged neural signatures associated with encoding the ***task-irrelevant stimuli***, we also looked at how the neural encoding of ***attended speech*** was affected by the type of task-irrelevant speech it was paired with. In line with previous MEG studies, the speech-tracking response (estimated using TRFs) was localized to auditory temporal

regions bilaterally and left inferior frontal regions [9,127,128]. The speech tracking response in auditory regions was similar in both conditions, however the response in left inferior-frontal cortex was modulated by the type of task-irrelevant speech presented and was enhanced when task-irrelevant speech was Structured vs. when it was Non-Structured. This pattern highlights the nature of the competition for resources triggered by concurrent stimuli. When the task-irrelevant stimulus was Non-Structured, even though it was comprised of individual phonetic-acoustic units, it did not contain meaningful linguistic information and therefore did not require syntactic and semantic resources. However, the Structured task-irrelevant speech poses more of a competition, since it constitutes fully intelligible speech. Indeed, it is well established that intelligible task-irrelevant speech causes more competition and therefore are more distracting than non-intelligible speech [28–35]. A recent EEG study found that responses to both target and distractor speech are enhanced when the distractor was intelligible vs. unintelligible [129], although this may depend on the specific type of stimulus used [130]. However, in most studies it is difficult to ascertain the level(s) of processing where competing between the inputs occurs, and many effects can be explained by variation in the acoustic nature of maskers [131]. The current study is unique in that all low-level features of Structured and Non-Structured speech stimuli were perfectly controlled, allowing us to demonstrate that interference goes beyond the phonetic-acoustic level and also occurs at higher linguistic levels. The current findings of modulation of the speech tracking response to attended speech is enhanced when faced with a Structured task-irrelevant speech, and that this effect is observed in the same left inferior-frontal brain region where we observed tracking of the phrase-structure of task-irrelevant speech, pinpoints the locus of this competition to these dedicated speech-processing regions, above and beyond any sensory-level competition [103,104,132]. Specifically, they suggests that the enhanced speech tracking response in IFG reflects the investment of additional listening effort for comprehending the task-relevant speech [88,90,133].

Conclusions

The current study contributes to ongoing efforts to understand how the brain deals with the abundance of auditory inputs in our environment. Our results indicate that eventhough top-down attention effectively enables listeners to focus on a particular task-relevant source of input (speech in this case), this prioritization can be affected by the nature of task-irrelevant sounds. Specifically, we find that when the latter constitutes meaningful speech, left fronto-temporal speech-processing regions are engaged in processing both stimuli, potentially leading to competition for resources and more effortful listening. Additional brain regions, such as the PPC, are also engaged in representing some aspects of the linguistic structure of task-irrelevant

speech, we which interpret as maintaining a representation of what goes on in the 'rest of the environment', in case something important arises. Importantly, similar interactions between the structure of task-irrelevant sounds and responses to attended sounds have been previously demonstrated for non-verbal stimuli as well [134]. Together, this highlights the fact that attentional selection is not an all-or-none processes, but rather is a dynamic process of balancing the resources allocated to competing input, which is highly affected by the specific perceptual, cognitive and environmental aspects of a given task.

Materials and Methods

Participants

We measured MEG recordings from 30 (18 females) native Hebrew speakers. Participants were adult volunteers, ages ranging between 18 and 34 (M=24.8, SD=±4.2). All were right-handed, with self-reported normal hearing and with no history of neurological disorders or ADHD. The study was approved by the IRB committee at Bar-Ilan University and all participants provided their written consent for participation prior to the experiment.

Natural Speech (attended)

Natural speech stimuli were narratives from publicly available Hebrew podcasts and short audio stories (duration: 44.53±3.23 seconds). Recordings that were originally recorded in a female voice were edited using the change-gender function in Praat (Boersma P. 2011, www.praat.org) so that all recordings were presented in a male voice, and sound intensity was equate across all stimuli. These natural speech narratives served as the to-be-attended stimuli in the experiment.

Frequency-tagged Speech (task-irrelevant)

A bank of individually recorded Hebrew syllables were used to create two sets of isochronous speech sequences. Single syllables were recorded in random order by a male actor, and remaining prosodic cues were removed using pitch normalization in Praat. Additional sound editing was performed to adjust the length of each syllable to be precisely 250 ms either by truncation or silence padding at the end (original mean duration 243.6±64.3 ms, range 168–397 ms). In case of truncation, a fading out effect was applied to the last 25 ms to avoid clicks. Sound intensity was then manually equated for all syllables.

These syllables were concatenated to create long sequences using custom-written scripts in MATLAB (The MathWorks), equated in length to those of the natural speech segments (44.53±3.23). Sequences could either be Non-Structured, with syllables presented in a fully random order without creating meaningful linguistic units, or they could be linguistically Structured. Structured sequences were formed, using the same procedure as in a previous study from our group [55], as follows: Every two syllables formed a word, every two words formed a phrase, and every two phrases formed a sentence. Because syllables were grouped hierarchically into linguistic constituents with no additional acoustic gaps inserted between them, different linguistic hierarchies are associated with fixed periodicities throughout the stimuli (syllables at 4

Hz, words at 2 Hz, phrases at 1 Hz, and sentences at 0.5 Hz; Figure 1b). Structured stimuli also contained no prosodic cues or other low-level acoustic indications for boundaries between linguistics structures, nor did Structured sentences include rhymes, passive form of verbs, or arousing semantic content. See Supplementary Material for more information on the construction of Structured and Non-Structured stimuli.

The modulation spectrum of both types of task-irrelevant stimuli is shown in Figure 1d. It was calculated using a procedure analogous to the spectral analysis performed on the MEG data, in order to ensure maximal comparability between the spectrum of the stimuli and the spectrum of the neural response. Specifically, (1) the broadband envelope of each sequence was extracted by taking the root-mean-square of the audio (10-ms smoothing window); (2) the envelope was segmented into 8-second long segments, which was identical to the segmentation of the MEG data; (3) a fast Fourier transform (FFT) was applied to each segment; and (4) averaged across segments. As expected, both stimuli contained a prominent peak at 4Hz, corresponding to the syllable rate. The Structured stimuli also contain a smaller peak at 2Hz, which corresponds to the word-rate. This is an undesirable side-effect of the frequency tagging approach, since ideally these stimuli should not contain any energy at frequencies other than the syllable-rate. As shown in the Supplementary Material, the 2Hz peak in the modulation spectrum reflects the fact that a consistently different subset of syllables occurs at each position within the sequence (e.g. at the beginning\end of words; for similar acoustic effects when using frequency-tagging of multi-syllable words see [121]. A similar 2Hz peaks is not observed in the Non-Structured condition, where the syllables are randomly positioned throughout all stimuli. Given this difference in the modulation spectrum, if we were to observe a 2Hz peak in the neural response to Structured vs. Non-Structured stimuli, this would not necessarily provide conclusive evidence for linguistic 'word-level' encoding (although see [55] and Supplementary Material for a way to control for this). As it happened, in the current dataset we did not see a 2Hz peak in the neural response in either condition (see Results), therefore this caveat did not affect the interpretability of the data in this specific instance. Importantly, neither the Structured nor the Non-Structured stimuli contained peaks at frequencies corresponding to other linguistic levels (1Hz and 0.5Hz), hence comparison of neural responses at these frequencies remained experimentally valid.

Experimental Procedure

The experiment used a dichotic listening paradigm, in which participants were instructed to attend to a narrative of natural Hebrew speech presented to one ear, and to ignore input from

the other ear where either Structured or Non-Structured isochronous task-irrelevant speech was presented. The experiment included a total of 30 trials (44.53±3.23 sec long), and participants were informed at the beginning of each trial which ear to attend to, which was counterbalanced across trials. The sound intensity of isochronous task-irrelevant stimuli increased gradually during the first three seconds of each trial, to avoid inadvertent hints regrading word-boundaries, and the start of each trial was excluded from data analysis. After each trial, participants answered four multiple choice questions about the content of the narrative they had attended to. Responses were recorded using button presses. The onset of the next trial was self-paced.

Additional Tasks

Based on previous experience, the Structured speech materials are not immediately recognizable as Hebrew speech and require some familiarization. Hence, to ensure that all participants could identify these as speech, they underwent a familiarization stage prior to the start of the main experiment, inside the MEG. In this stage, participants heard sequences of 8 isochronous syllables, which were either Structured – forming a single sentence – or Non-Structured. After each trial participants were asked to repeat the sequence out loud. The familiarity stage continued until participants correctly repeated five stimuli of each type. Structured and Non-Structured stimuli were presented in random order.

At the end of the experiment a short auditory localizer task was performed. The localizer included hearing tones in five different frequencies: 400Hz, 550Hz, 700Hz, 850Hz, 1000Hz, all 200 ms long. The tones were presented with random ISIs: 500ms, 700ms, 1000ms, 1200ms, 1400ms, 1600ms, 1800ms, and 2000ms. Participants listened to the tones passively and were instructed only to focus on the fixation mark in the center of the screen.

MEG Data Acquisition

MEG recordings were conducted with a whole-head, 248-channel magnetometer array (4D Neuroimaging, Magnes 3600 WH) in a magnetically shielded room at the Electromagnetic Brain Imaging Unit, Bar-Ilan University. A series of magnetometer and gradiometer reference coils located above the signal coils were used to record and subtract environmental noise. The location of the head with respect to the sensors was determined by measuring the magnetic field produced by small currents delivered to five head coils attached to the scalp. Before the experimental session, the position of head coils was digitized in relation to three anatomical landmarks (left and right preauricular points and nasion). The data was acquired at a sample rate of 1017.3 Hz and an online 0.1 to 200 Hz band-pass filter was applied. The 50Hz power line noise

fluctuations were recorded directly from the power line as well as vibrations using a set of accelerometers attached to the sensor in order to remove the artifacts on the MEG recordings.

MEG Preprocessing

Preprocessing was performed in MATLAB (The MathWorks) using the FieldTrip toolbox (www.fieldtriptoolbox.org). Outlier trials were identified manually by visual inspection and were excluded from analysis. Using independent component analysis (ICA) we removed eye movements (EOG), heartbeat and vibrations of the building. The clean data was then segmented into 8-second-long segments, which corresponds to four sentences in the Structured condition. Critically, these segments were perfectly aligned such that they all start with the onset of a syllable, which in the Structured condition will also be the onset of a sentence.

Source Estimation

Source estimation was performed in Python (www.python.org) using the MNE-python platform [136,137]. Source modeling was performed on the pre-processed MEG data, by computing Minimum-Norm Estimates (MNEs). In order to calculate the forward solution, and constrain source locations to the cortical surface, we constructed a Boundary Element Model (BEM) for each participant. BEM was calculated using the participants' head shape and location relative to the MEG sensors, which was co-registered to a MRI template (FreeSurfer; surfer.nmr.mgh.harvard.edu). Then, the cortical surface of each participant was decimated to 8,194 source locations per hemisphere with at least 5-mm spacing between adjacent locations. A noise covariance matrix was estimated using the inter-trial intervals in the localizer task (see Additional Tasks), that is, periods when no auditory stimuli were presented. Then, an inverse operator was computed based on the forward solution and the noise covariance matrix, and was used to estimate the activity at each source location. For visualizing the current estimates on the cortical surface, we used dynamic Statistical Parametric Map (dSPM), which is an F-statistic calculated at each voxel and indicating the relationship between MNE amplitude estimations and the noise covariance [138]. Finally, individual cortical surfaces were morphed onto a common brain, with 10,242 dipoles per hemisphere [139], in order to compensate for inter-subject differences.

MEG Data Analysis

Spectral Analysis

Scalp level

Inter-trial phase coherence (ITPC) was calculated on the clean and segmented data. To this end, we applied a Fast Fourier Transform (FFT) to individual 8-second long segments and extracted the phase component at each frequency (from 0.1 to 15 Hz, with a 0.125Hz step). ITPC at each sensor was calculated as the sum of absolute phases across N segments:

$$ITPC = \frac{1}{N}\left|\sum_{k=1}^{N} e^{i*\phi_k}\right|.$$

This was performed separately for the Structured and Non-Structured conditions. We then compared the ITPC spectra between the two conditions at the group-level, focusing specifically on four frequencies of interest (FOI): 4Hz, 2Hz, 1Hz and 0.5Hz which correspond to the four linguistic levels present in the Structured stimuli (syllables, words, phrases and sentences, respectively). In order to determine whether responses at these frequencies differed significantly between conditions we performed a permutation test. In each permutation, the labels of two conditions were randomly switched in half the participants, and a paired t-test was performed. This was repeated 1,000 times, creating a null-distribution of t-values for this paired comparison, separately for each of the FOIs. The t-values of the real comparisons were evaluated relative to this null-distribution, and were considered significant if they fell within the top 5%^{tile} (one-way comparison, given our a-priori prediction that peaks in the Structured condition would be higher than in the Non-Structured condition). This procedure was performed on the average ITPC across all sensors, to avoid the need to correct for multiple comparisons.

Source level

Statistical comparison of responses at the source-level in the Structured and Non-Structured conditions focused only on the peaks that showed a significant difference between conditions at the scalp level (in this case, the peak at 1Hz). In order to determine which brain-regions contributed to this effect we used 22 pre-defined ROIs in each hemisphere, identified based on multi-modal anatomical and functional parcellation [140]. We calculated the mean ITPC value in each ROI, across participant and conditions, and tested for significant differences between them using a permutation test, which also corrected for multiple comparisons. As in the scalp-data, the permutation test was based on randomly switching the labels between conditions for half of the participants and conducting a paired t-test within each ROI. In each permutation

we identified ROIs that passed a statistical threshold for a paired t-test ($p<0.05$) and the sum of their t-values was used as a global statistic. This procedure was repeated 1,000 times, creating a null distribution for this global statistic. A similar procedure was applied to the real data, and if the global statistic (sum of t-values in the ROIs that passed an uncorrected threshold of $p<0.05$) fell within the top 5%^{tile} of the null distribution, the entire pattern could be considered statistically significant. This procedure was conducted separately within each hemisphere.

Speech-Tracking Analysis

Speech-tracking analysis was performed in order to estimate the neural response to the natural speech that served as the to-be-attended stimulus. To this end, we estimated the Temporal Response Function (TRF), which is a linear transfer-function expressing the relationship between features of the presented speech stimulus $s(t)$ and the recorded neural response r(t). TRFs were estimated using normalized reverse correlation as implemented in the STRFpak Matlab toolbox (strfpak.berkeley.edu) and adapted for MEG data [9]. Tolerance and sparseness factors were determined using a jackknife cross-validation procedure, to minimize effects of over-fitting. In this procedure, given a total of N trials, a TRF is estimated between $s(t)$ and $r(t)$ derived from N-1 trials, and this estimate is used to predict the neural response to the left-out stimulus. The tolerance and sparseness factors that best predicted the actual recorded neural signal (predictive power estimated using Pearson's correlation) were selected based on scalp-level TRF analysis (collapsed across conditions), and these were also used when repeating the analysis on the source-level data [141]. The predictive power of the TRF model was also evaluated statistically by comparing it to a null-distribution obtain from repeating the procedure on 1,000 permutations of mismatched $s^*(t)$ and $r^*(t)$.

TRFs to the attended natural speech were estimated separately for trials in which the task-irrelevant speech was Structured vs. Non-Structured. TRFs in these two conditions were then compared statistically to evaluate the effect of the distractor type on neural encoding of attended speech. For scalp level TRFs we used a spatial-temporal clustering permutation test to identify the time-windows where the TRFs differed significantly between conditions (fieldtrip; first level stat $p<0.05$, cluster corrected). We then turned to the source-level TRFs to further test which brain regions showed significant difference between conditions, by estimating TRFs in the same 22 pre-defined ROIs in each hemisphere used above. TRFs in the Structured vs. Non-Structured conditions were compared using t-tests in 20-ms long windows (focusing only on the 70-180ms time window which was found to be significant in the scalp-level analysis) and corrected for multiple comparisons using spatial-temporal clustering permutation test.

Acknowledgements

This work was funded by Binational Science Foundation (BSF) grant # 2015385. We would like to thank Dr. Nai Ding for helpful comments on a previous version of this paper.

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Figures

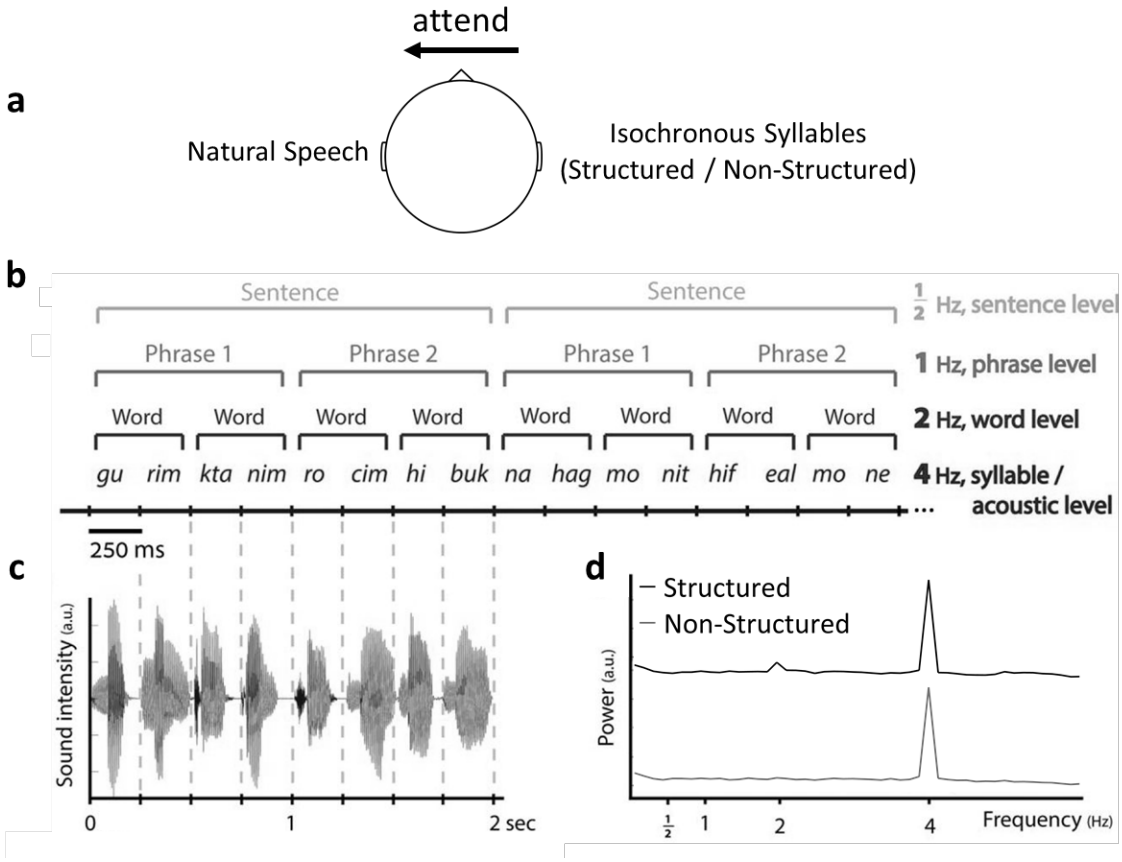


Figure 1. a, Dichotic paradigm experiment. Participants were instructed to attended right or left ear (counterbalanced) and ignore the other. Attended stimuli was always natural Hebrew speech, with multiple answers questions about the content at the end of each trial. The task-irrelevant ear was always presented with hierarchical frequency-tagging stimuli in two conditions: Structured and Non-Structured. **b**, Example of intelligible (Structured) speech composed of 250 ms syllables in which 4 levels of information are differentiated based on their rate: acoustic/syllabic, word, phrasal, and sentential rates (at 4, 2, 1, and 0.5 Hz, respectively). Translation of the Hebrew sentences in the example: "Small puppies want a hug" and "A taxi driver turned on the meter." Control stimuli were unintelligible (Non-Structured) syllable sequences with similar syllabic rate of 4Hz. **c**, Representative sound wave of a single sentence (2s). Sound intensity fluctuates at the rate of 4 Hz. **d**, Induced power spectrum of 50 stimuli soundwave envelope per condition. * Figure adapted from Makov et al. 2017.

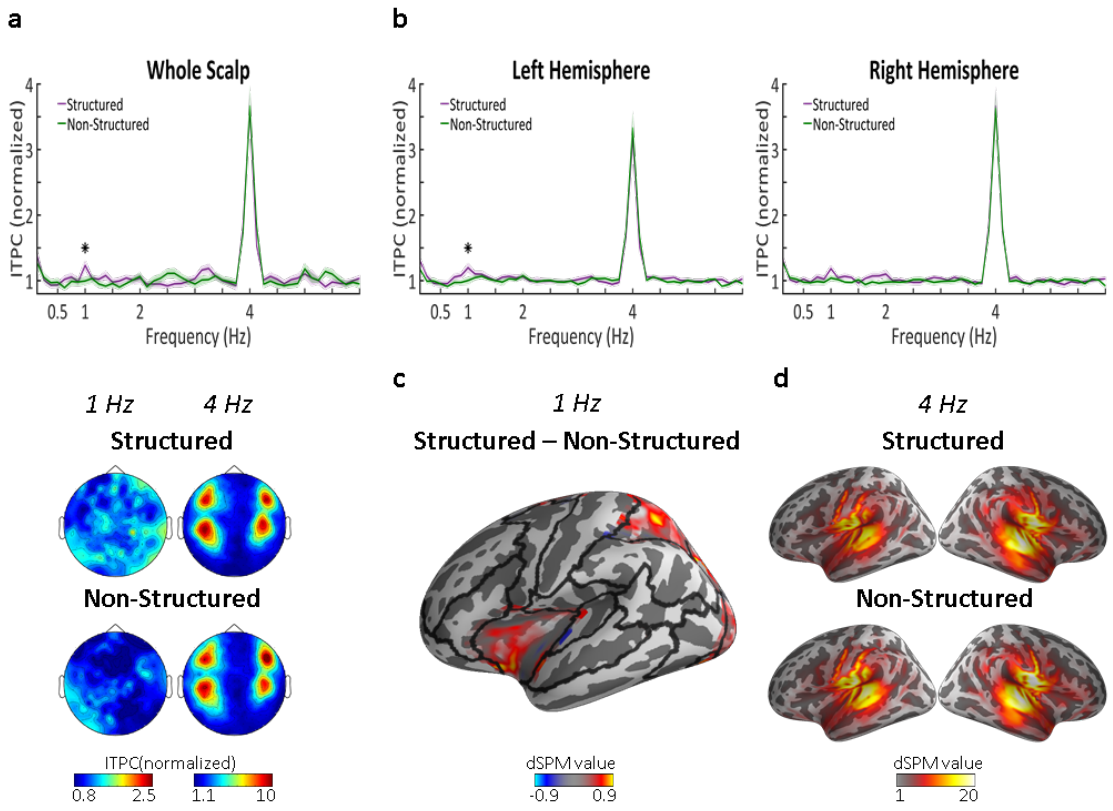


Figure 2. Neural tracking of linguistic structures in task-irrelevant speech. **a**, Top panel shows the ITPC spectrum at the scalp level (average across all electrodes) in response to Structured (purple) and Non-Structured (green) task-irrelevant speech. Shaded areas indicate SEM across participants (n=29). Asterisk represents statistically significant difference ($p<0.05$) between conditions, indicating a significant response at 1Hz for Structured task-irrelevant speech, which corresponds to the phrase-level. Bottom panel shows the scalp-topography of ITPC at 4Hz and 1 Hz in the two conditions. **b**, ITPC spectrum at the source level, averaged across all voxels in each hemisphere. Shaded highlights denote SEM across participants (n=23). Asterisk represents statistically significant difference ($p<0.05$) between conditions, indicating a significant response at 1Hz for Structured task-irrelevant speech in the left, but not right hemisphere. **c**, Source-level map on a central inflated brain depicting the ROIs in the left hemisphere where significant differences in ITPC at 1Hz were found for Structured vs. Non-Structured task-irrelevant speech. Black lines indicate the parcellation into the 22 ROIs used for source-level analysis. **d**, Source-level maps showing localization of the syllabic rate response (4 Hz) in both conditions.

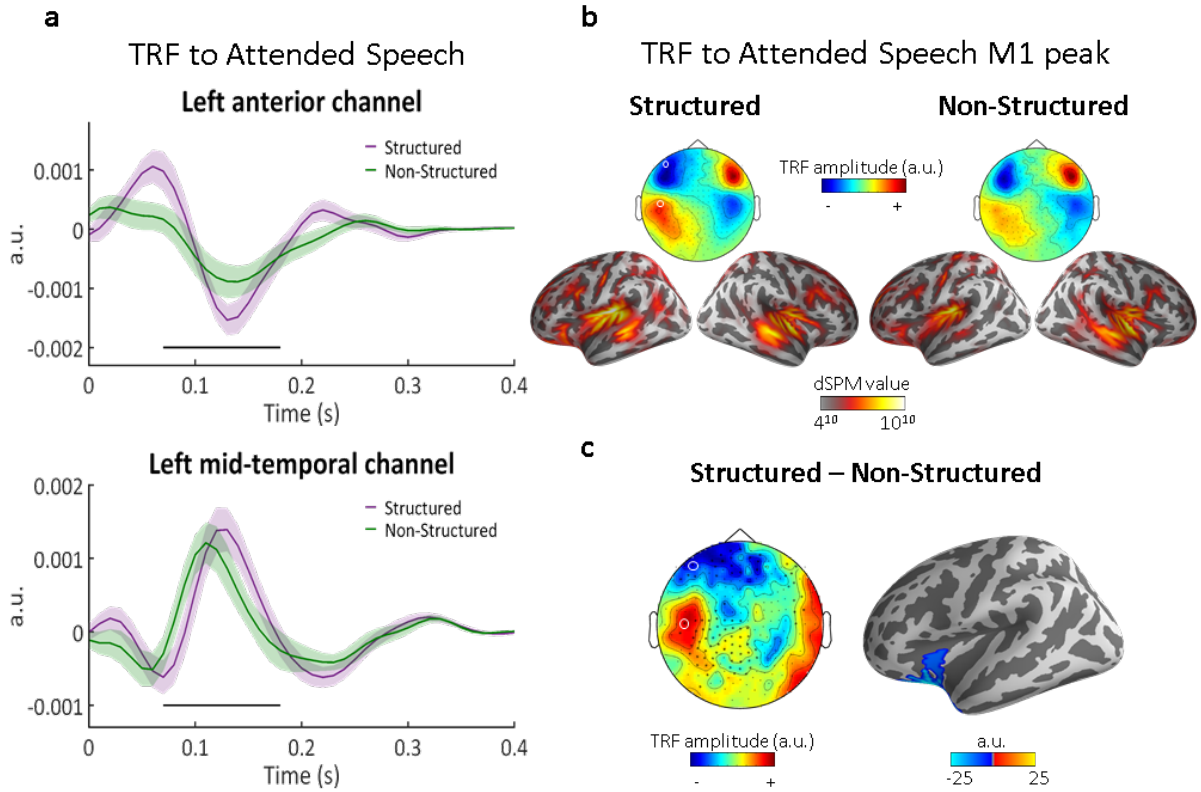


Figure 3. a, TRF examples from two sensors (marked panel b), showing the positive and negative poles of the TRF over the left hemisphere. Shaded highlights denote SEM across participants. Black line indicates the time points where the difference between conditions was significant (spatio-temporal cluster corrected). **b**, topographies (top) and source estimations (bottom) for each condition at M1 peak (140 ms). **c**, **left,** topography of the difference between conditions (Structured – Non-Structured) at the M1 peak (140 ms). Asterisks indicate the MEG channels where this difference was significant (cluster corrected). **right,** significant cluster at the source level.

Supplementary Materials

The modulation spectrum of Structured speech stimuli used in this study featured a prominent peak is at 4Hz, corresponding to the syllable rate, and an additional smaller peak at 2Hz. Since the stimuli were built by concatenating 250-ms long syllables, while taking care **not** to introduce any additional acoustic events that would introduce other rhythmic regularities (such as systematic gaps between words; Buiatti et al. 2009), we hypothesized that it may be related to the **order** of the syllables within the Structured sequences. Specifically, since our Structured stimuli was comprised of bi-syllabic Hebrew words, there may be a systematic difference in the envelope-shape of syllables at the beginning vs. end of words. For example, in the materials used here, it was indeed more common to start a word with a CV syllable than to end with one (Figure S1 and S2a). This, in turn, could lead to subtle yet systematic differences in the envelope-shape at even vs. odd positions in the stimulus, particularly after averaging across sentences/trials, resulting in a 2Hz peak in the modulation spectrum. A recent study by Luo and Ding (2020) nicely demonstrate that an acoustics-driven 2Hz peak can be induced simply by amplifying every second syllable in multi-syllable words.

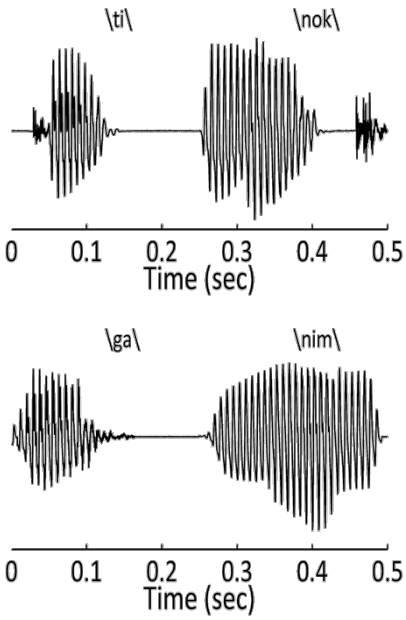


Figure S1. Two examples of start and end syllables for bi-syllabic Hebrew words. This illustrates the natural differences in envelope-shape for different syllables. If short CV syllables systematically occur at the start vs. end of words, this can potentially create a 2Hz peak in the modulation spectrum.

To better understand the origin of the 2Hz peak in our Structured stimuli we ran several simulations, testing how the order of the syllables within the sequence affected modulation spectrum. First, we created Position-Controlled Stimuli (Figure S2b), which were pseudo-sentences comprised of the same syllables as the Structured speech, but ordered in a manner that did not create linguistic meaning. Importantly, randomization was performed in a manner so that each syllable maintained the same position it had in the original sentences. For example, if

the syllable /gu/ was the first in original Sentence #1 and the syllable /buk/ was the last, then in the Position-Controlled stimuli these two syllables will still be first or last, respectively, but will no longer be part of the same pseudo-sentence (see concrete examples in Figure S2b). In this manner, the average audio-envelope across sentences is still identical to the Structured materials, but the stimuli no longer carry linguistic meaning.

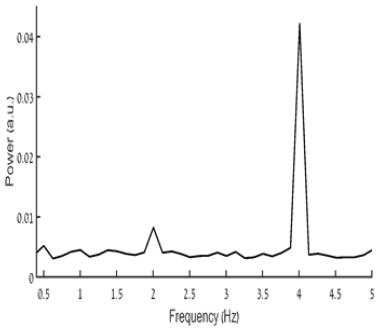
The same procedure was used for calculating the modulation spectrum as were applied to the original Structured Stimuli (see Methods for full details). Briefly, a total of 52 pseudo-sentences were constructed and randomly concatenated to form 50 sequences (56-seconds long). To stay faithful to the analysis procedure applied later to the MEG data, sequences were then divided into 8-second epochs, the envelope was extracted and FFT was applied to each epoch. The modulation spectrum is the result of averaging the spectrum across all epochs. We find that, indeed, the modulation spectrum of the original Structured materials and the Position-Controlled materials are basically identical, both containing similar peaks at 4Hz and 2Hz. This supports our hypothesis that the 2Hz peak stemmed from a natural asymmetry in the type of syllables that occur in start vs. end positions of bi-syllabic words (at least in Hebrew). We note that this type of Position-Controlled stimuli were used by us as Non-Structured stimuli in a previous study [55], and this is likely a more optimal choice as a control stimuli for future studies, as it allows to more confidently attribute differences at 2Hz in the neural response between Structured and Position-Controlled Non-Structured stimuli to linguistic, rather than acoustic, effects.

We next ran two additional simulations to determine what form of syllable randomization eliminates the 2Hz peak. We found that when creating pseudo-sentences where syllables are completely randomized and not constrained by position, the 2-Hz peak is substantially reduced (Figure S2c). However, in this case we used a Fixed set of 52 pseudo-sentences to form sequences of stimuli. When we further relaxed this constraint, and allowed different randomization in different sequences (Non-Fixed Randomized stimuli; Figure S2d), the 2Hz peak was completely eliminated. The latter is akin to the Non-Structured stimuli used in the current experiment, and hence they were, in fact, not fully controlled at the acoustic level for 2Hz modulations.

That said, since we did not in fact see any peak in the neural data at 2Hz, and the effect we did find was at 1Hz (which *is* controlled across conditions), this caveat does not affect the validity of the results reported here. Future studies using this hierarchical frequency-tagging approach should take care to equate the modulation spectrum of experimental and control stimuli on this dimension as well (as was done by Makov et al. 2017).

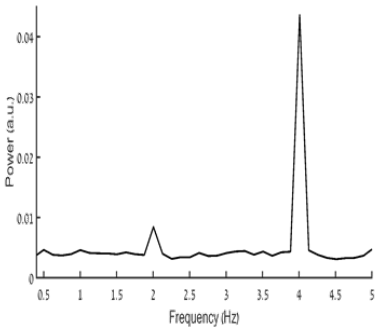
a Linguistically Structured Stimuli

Position:	#1	#2	#3	#4	#5	#6	#7	#8
Sentence 1	gu	rim	kta	nim	ro	cim	xi	buk
Sentence 2	sha	nim	ra	bot	xal	fu	ma	her
Sentence 3	ko	sem	za	ken	ish	lof	sha	fan
Sentence 4	yal	dei	ha	gan	xib	ru	si	pur
Sentence 5	ti	nok	ma	tok	sha	ta	xa	lav



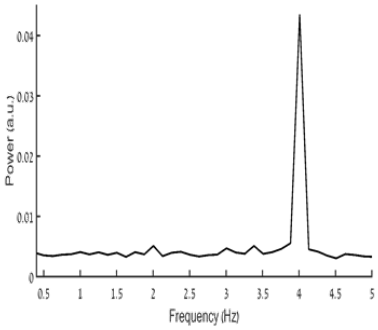
b Position-Controlled Stimuli (Linguistically Non-Structured)

Position:	#1	#2	#3	#4	#5	#6	#7	#8
Sentence 1	ti	nim	za	nim	ish	fu	xi	lav
Sentence 2	sha	nok	ha	bot	sha	lof	si	fan
Sentence 3	gu	dei	ma	ken	xal	cim	sha	her
Sentence 4	ko	rim	ra	tok	ro	ru	xa	pur
Sentence 5	yal	sem	kta	gan	xib	ta	ma	buk



c Fixed Randomized Stimuli (Linguistically Non-Structured)

Position:	#1	#2	#3	#4	#5	#6	#7	#8
Sentence 1	sha	ti	za	xal	gu	dei	ken	ma
Sentence 2	rim	nim	gan	buk	tok	ko	xib	cim
Sentence 3	yal	sha	nim	sem	bot	si	nok	sha
Sentence 4	ra	pur	ta	ha	kta	ish	ma	ru
Sentence 5	fan	xi	lav	xa	her	ro	fu	lof



d Non-Fixed Randomized Stimuli (Linguistically Non-Structured)

Trial 1	#1	#2	#3	#4	#5	#6	#7	#8
Sentence 1	sha	ti	za	xal	gu	dei	ken	ma
Sentence 2	rim	nim	gan	buk	tok	ko	xib	cim
Sentence 3	yal	sha	nim	sem	bot	si	nok	sha
Sentence 4	ra	pur	ta	ha	kta	ish	ma	ru
Sentence 5	fan	xi	lav	xa	her	ro	fu	lof

Trial 2	#1	#2	#3	#4	#5	#6	#7	#8
Sentence 1	xib	bot	ken	sha	gu	fan	ra	ro
Sentence 2	her	rim	tok	cim	ko	yal	pur	lof
Sentence 3	sha	ru	xi	xal	dei	xa	ish	fu
Sentence 4	yish	za	gan	te	ma	nim	ti	ha
Sentence 5	kta	lav	nim	sem	si	ma	buk	nok

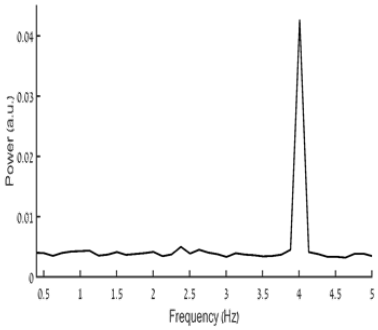


Figure S2. The effects of syllable-order on the modulation spectrum. Each panel shows examples for sentences/pseudo-sentence constructed in different ways (left) and the resulting modulation spectrum for this type of stimulus (right). **a**, Examples of five Structured sentences used in the current study. **b**, Example of Position-Controlled pseudo-sentences, where the syllables used in the Structured sentences are randomized across pseudo-sentences, but maintain the same position as in the Structured sentences. **c**, Examples of Fixed Randomized Stimuli, where a set of pseudo-sentences are constructed through random assignment of syllables (with no position-constraints), and these fixed pseudo-sentences are used to construct all the stimuli across trials. **d**, Examples of Non-Fixed Randomized Stimuli, where different randomization of syllables is used to construct stimuli in each trial.