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Understanding Neural Signals related to Speech Processing in Humans During Sleep

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Abstract

Many cognitive processes are surprisingly preserved during sleep, including the processing of basic language stimuli. However, whether the sleeping brain can process complex, natural speech is not yet known. The present study used regularized linear regression to understand which features of narrative speech, ranging from low-level acoustic information to higher-level linguistic information, are processed during sleep. Participants were exposed to an intact and scrambled narrative story while they were napping or lying awake. Temporal response functions (TRFs) mapped the relationship between participants' EEG neural responses and the (1) auditory envelope, (2) word onsets and (3) semantic dissimilarity of words. For all three analyses, delayed but statistically similar TRF components were observed during sleep and wake. These findings suggest that the sleeping brain is capable of low-level auditory processing, speech segmentation and semantic processing of narrative speech. These findings highlight that natural language processing remains remarkably intact during sleep.

Keywords

Sleep; Language Processing; Electroencephalography; Linear Regression; Natural Speech; Consciousness

Summary for Lay Audience

The brain is known to monitor its surroundings for important and dangerous stimuli during sleep. Previous research has shown that the sleeping brain is able to process some aspects of language during sleep. However, it is still not yet known which features of *natural,* continuous speech are processed during sleep. First, we aimed to examine if the brain can process the acoustic information of a natural speech source during sleep. Furthermore, we aimed to examine if the sleeping brain can segment the words uttered during natural speech. Finally, we aimed to determine if the brain can extract and understand the meanings of words in natural speech during sleep.

Participants were exposed to an excerpt from an audiobook called J.D. Salinger's *Pretty Mouth and Green My Eyes* and their brain activity was recorded, while they were either napping or lying awake in a bed. They were also exposed to a scrambled version of the excerpt that acted as a means of comparison when analyzing the participants' brain activity. A relatively new analytical method was used to associate the participants' brain activity with the acoustic audio information, the beginnings of words, and the meanings of the individual words in the natural speech stream. The results indicated that sleeping and awake participants exhibited similar brain activity patterns in association with the acoustic information, the beginnings of words, and the meanings of words conveyed in the audio excerpt. However, the key neural components associated with these processes occurred later for sleeping participants, as compared to wake. This indicates that the sleeping brain not only processes the low-level acoustic information of a natural speech stream during sleep but can also segment and extract the meanings of words in natural speech. These results are among the first to display that the brain can understand key high-level conceptual information in natural speech during sleep, demonstrating the advanced capabilities of the sleeping brain.

Co-Authorship Statement

The EEG data in this investigation were collected as part of a previous Masters' project performed and submitted by Sarah Hollywood in 2020 at Western University. The EEG data had not been previously analyzed. The current Masters' thesis involves performing novel data analyses on this dataset.

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1 Introduction

Sleep is widely considered to represent an altered state of consciousness, marked by a reversible reduction in responsiveness to external stimuli and conscious awareness (Rasch & Born, 2013). Despite the reduction in conscious awareness, previous research has shown that the brain continuously monitors its environment for important salient events during sleep (Formby, 1967). For example, researchers have shown that the sleeping brain distinguishes between unique and repetitive tones (Bastuji et al., 1995), discriminates between emotionally salient and neutral stimuli (Portas et al., 2000), and even tracks meaningful speech to a greater extent than nonmeaningful speech (Legendre et al., 2019). However, we do not yet understand *which* features or types of information can be extracted from continuous speech during sleep.

Speech is a dynamic and complex stimulus that is processed at different levels, ranging from low level auditory processing to higher level semantic processing (Brodbeck & Simon, 2020). Due to its complexity, most electrophysiological studies of speech processing have focused on characterizing the brain's response to brief, discrete stimuli, such as semantically incongruous words within specially constructed sentences (Broderick et al., 2018). Relatively few studies have examined neural processing of continuous, narrative speech in general (Brodbeck et al., 2018; Broderick et al., 2018), and almost no studies have examined these processes during sleep. As a result, very little is known about the sleeping brain's ability to extract key features of natural, connected speech. Specifically, the question of *which* features of natural, narrative speech—which range from low-level acoustic information to higher-level linguistic properties such as semantics—are processed during sleep remains unaddressed. The goal of this thesis project was to bridge this gap in knowledge by using novel analytical methods to identify the features of natural, narrative speech that are detected by the brain during sleep.

1.1 Sleep Architecture

Sleep can be classified into two major categories: rapid eye movement (REM) and non-rapid eye movement (NREM) sleep. REM sleep is dominated by low amplitude, high frequency neural activity and is the period of sleep most strongly associated with dreaming, whereas NREM sleep is often associated with high amplitude, low frequency neural activity and consists primarily of nonvisual thoughts (McCarley, 2007). NREM sleep can be further broken down into three substages: stage 1 (NREM1), stage 2 (NREM2), and stage 3 (NREM3) sleep. Each stage of sleep is characterized by different electroencephalography (EEG) waveforms (see Figure 1).

NREM1 is considered the lightest stage of sleep and is marked by decreased alpha (8-13 Hz EEG activity) waves and the emergence of theta waves (4-8 Hz EEG activity) (Malhotra & Avidan, 2013). Individuals who wake up from NREM1 sleep are often unaware of having fallen asleep and tend to report that they did not fall asleep at all (Malhotra & Avidan, 2013). NREM2 sleep also contains theta activity but is especially characterized by the occurrences of unique EEG waveforms called sleep spindles and K-complexes (Malhotra & Avidan, 2013). Sleep spindles are defined as quick bursts of neural activity between 11-16 Hz with a duration between 0.5 – 1.5 seconds (Gennaro & Ferrara, 2003). Sleep spindles have been linked to neural plasticity and both sleep-dependent declarative and procedural memory consolidation (Ulrich, 2016). K-complexes are characterized by a large, abrupt onset EEG negativity, followed by a longer lasting positivity (Roth et al., 1956). A proposed role for K-complexes includes the protection against arousals from non-salient stimuli (Colrain, 2005). The third stage of NREM sleep (NREM3) is also known as slow wave sleep and is characterized by very slow oscillatory (1-4 Hz) and large amplitude ($\geq$ 75 μV) delta waves (Malhotra & Avidan, 2013). Slow wave sleep is believed to play a key role in cerebral recovery and restoration in humans, along with the consolidation of long-term memories from the hippocampus to neocortical sites (Roth, 2009; Diekelmann & Born, 2010). Finally, REM sleep is characterized by low amplitude, high frequency EEG activity, comparable to the EEG activity seen in wakefulness, along with rapid eye movements (Malhotra & Avidan, 2013). This stage is often identified as the dreaming phase of sleep and has been linked to the consolidation of emotional memories (Hutchison & Rathore, 2015). The brain cycles through the three stages of NREM sleep and REM sleep in a sequential order. Each sleep cycle lasts about 90 mins in length and tend to follow the order of NREM1, NREM2, NREM3 and REM sleep. Throughout a typical night sleep, the early cycles tend to be dominated by slow-wave sleep, whereas later cycles tend to be dominated by REM sleep (Lee-Chiong, 2011).

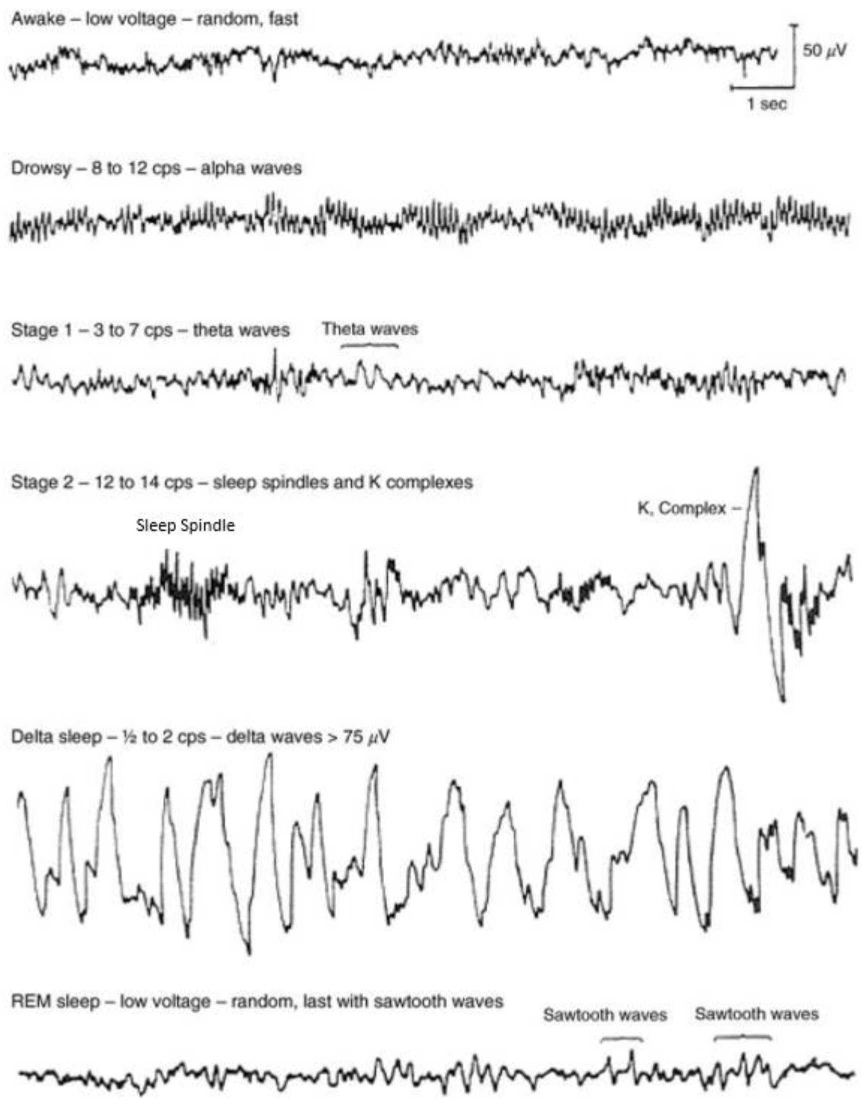

Figure 1. EEG waveforms of sleep

Characteristic EEG waveforms observed during wakefulness and each sleep stage (from Binder et al., 2009).

1.2 Neural Processing of Natural Speech

Natural speech is a highly complex and layered stimulus. To understand speech, humans must extract information from the speech signal at many different levels of analysis, including at the acoustic level, the word or lexical level, and the semantic level. Low-level auditory processing of speech refers to the brain's ability to analyze the acoustic speech signal based on its basic auditory features, such as pitch, intensity, and timbre (Melara & Marks, 1990). Speech segmentation is the process of identifying where one word ends and the next one begins in continuous speech (Sanders et al., 2002). Semantic processing refers to the processing of meaning, and often relies on relating the word that has been heard to words with similar meanings (Xu et al., 2017).

1.2.1 Auditory Processing During Sleep

Previous research has indicated that the brain is able to process low level auditory information not only while awake, but also during sleep. There have been a multitude of different paradigms and stimuli used to study the level of auditory processing occurring during sleep. For example, in one of the earliest studies to examine this question, Bastuji et al. (1995) used an oddball paradigm, in which participants were exposed to both frequent (90%) and deviant (10%) tones during both wake and nocturnal sleep. During wake, deviant stimuli elicited a prominent P300, a positive event-related potential at 300 ms after stimulus onset, in the parieto-central areas of the brain. During NREM2 and NREM3 sleep, both frequent and deviant tones elicited auditory evoked potentials that resembled K-complexes; however, the potentials to deviant responses were almost five times larger than potentials evoked to frequent tones. During REM and NREM1 sleep, only deviant tones elicited auditory evoked potentials at 344 ms, which resembled the P300 response seen in awake participants. Thus, although the exact neural signatures differed depending on sleep stage, the brain was able to detect auditory stimulus deviance during all stages of sleep, suggesting that at least some aspects of lower-level auditory processing are intact during sleep.

Like Bastuji and colleagues, Ruby et al. (2008) analyzed the brain's ability to process auditory deviancy during sleep but focused on the *mismatch negativity* to deviant sounds. The mismatch negativity is defined as the negative EEG waveform occurring at fronto-central sites at around 150 ms (Näätänen et al., 1985), which is proposed to reflect a mismatch between stored sensory memory representations and an incoming auditory stimulus. Frequent and deviant tones were played continuously throughout the night, and the mismatch negativity occurred to deviant tones during all stages of sleep. In addition, a P3b-like potential was evoked for deviant tones, but only during REM and NREM2 sleep (Ruby et al., 2008). As the P3b component is a subcomponent of the P300 component that has been linked to conscious processing, the researchers in this study proposed that this P3b potential reflected the processing of deviant tones that had been incorporated into the consciousness of a dream. This investigation confirms that auditory processing occurs in the brain during all stages of sleep, and the P3b finding suggests that additional auditory processing may occur during NREM2 and REM sleep.

There has also been single unit electrophysiological research on auditory processing occurring in the brain during sleep. Nir et al. (2015) recorded single unit and local field potential responses in primary auditory cortex in rats exposed to auditory stimulation during sleep and wake. Using an oddball paradigm to examine neuronal activity associated with processing deviant tones, the authors reported several findings that point to similarities in the processing of deviants between wake and sleep. First, the selectivity and magnitude of auditory evoked responses were similar for both wake and sleep. In addition, stimulus-specific adaptation occurred upon the onset of repetitive tones in both sleeping and awake rats. Furthermore, the strength of the adaptation effects was similar between sleep and wakefulness, signifying similar levels of auditory processing of the deviant tones. This investigation provides additional support for intact auditory processing at the single cell level in the brain during sleep.

Along with the detection of deviancy, researchers have demonstrated that the brain is able to process emotionally salient or meaningful auditory stimuli during sleep. Portas et al. (2000) used simultaneous functional magnetic resonance imaging (fMRI) and EEG to analyze the neural activity associated with auditory stimulation during sleep. The researchers presented participants with both pure tones (beeps) and the participant's first name, with the auditory stimuli matched in both intensity and duration. They discovered that auditory stimulation elicited bilateral activation in the auditory cortex, thalamus, and caudate nuclei across wake and NREM sleep. However, the prefrontal cortex and thalamus were less activated during NREM sleep compared to wake. Perhaps most interestingly, the left amygdala and the left prefrontal cortex experienced increased activation during NREM sleep when the participant's first name was played compared to the neutral tones. This confirms that not only is auditory processing primarily intact during sleep, some higher-level processing supporting the detection of relevant or meaningful stimuli can also occur.

1.2.2 Semantic Processing During Sleep

The previous studies provide evidence that the sleeping brain is able to detect both deviant as well as potentially meaningful or relevant stimuli, indicating that some relatively higher-level processes can occur during sleep. Building on these results, the next set of studies aimed to identify if this higher order processing is semantic in nature—that is, whether the brain can process the meanings of words during sleep. To investigate this question, most previous research has characterized the neural response to different types of linguistic stimuli during awake and sleep. For example, Perrin et al. (1999) compared the auditory evoked potentials elicited by participants' own names and seven other first names, during wakefulness, NREM2, and REM sleep. As expected, during wake, a positive parietal component was observed at 500 ms for all names, which was significantly enhanced to the participant's own name compared to the seven other random names. During NREM2 sleep, K-complexes were evoked for all names. The K-complexes were comprised of two biphasic consecutive waveforms. Interestingly, while the amplitude of the late section was identical for all stimuli, the early section of the K-complex was significantly higher after the participant's own name was presented. Specifically, there was a significantly greater amplitude for the positive wave in the first section of the K-complex at about 600 ms. These findings support the hypothesis that the brain can process the meaning and significance of certain auditory stimuli during sleep. However, these results do not provide conclusive evidence of semantic processing occurring in the brain during sleep, as the brain may be reacting to the individual's name differently due to its high frequency of exposure and/or its emotional valence.

Brualla et al. (1998) examined semantic processing during sleep more directly, using a semantic priming paradigm to test the depth of semantic processing occurring in the sleeping brain. During both wake and sleep, participants were exposed to a set of word-pairs, where half of the word-pairs were related (e.g., chicken-egg), and the other half were unrelated (e.g., watch-burger). As expected, during wake, a N400 event-related potential (ERP) was elicited for both the related and unrelated word-pairs, with the amplitude of the N400 greater for unrelated compared to related word pairs. The N400 component is a well-established ERP in literature that is known to be sensitive to the semantic relationships between words and their preceding contexts (Kutas & Hillyard, 1980, 1984; see Figure 2). During NREM2 sleep, a stronger negativity was also observed for unrelated word pairs compared to related word pairs, but at a later latency, around 680 ms (N680). This same effect was observed at 570 ms (N570) during REM sleep. Other ERP components such as the N200, P300, P1 have all been linked with longer latencies during sleep (Wesenten & Badia, 1988; Nielsen-Bohlman et al., 1991). The increased latency of ERP components during sleep was an interesting finding and may related to the increased slow oscillatory activity occurring in the brain during sleep. Despite some differences in amplitude and latency, these results indicate that an ERP semantic priming effect is maintained during sleep.

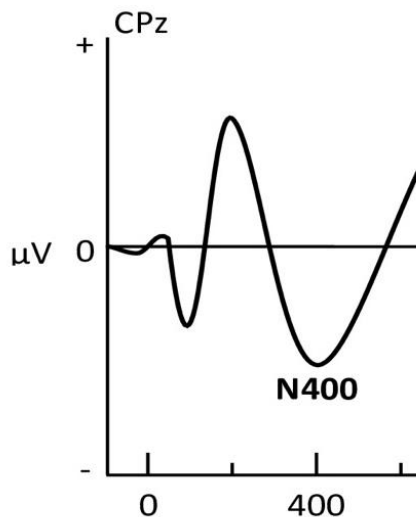

Figure 2. N400 ERP component

The characteristic N400 ERP component indicative of semantic processing (from Ledwidge, 2018).

Ibáñez et al. (2006) delved deeper into this topic by testing whether the sleeping brain can extract semantic information from full sentences, rather than just isolated word pairs. In this study, participants were presented with a variety of spoken sentences, where the last word of the sentence was either congruous or incongruous with the rest of the sentence. For example, if the phrase, "Something that flies and has a motor is a/an….", was played, an incongruous ending would be "bird", whereas a congruous ending would be "airplane". During both sleep and wake, the critical ending words elicited an N400-like component, whose amplitude varied as a function of congruency; the higher the degree of incongruency of the ending word to the rest of the sentence, the larger the amplitude of the N400 like component. Furthermore, the latency of the N400-like component was delayed to about 600 ms during sleep, relative to 400 ms during wake. Although the N400-like component showed a significantly decreased amplitude and delayed latency in the sleep condition, these results exemplify that semantic processing can occur at the sentence level during sleep.

Kouider et al. (2014) developed a novel paradigm to examine semantic processing and associated motor responses during sleep. First, during wake, participants were asked to classify certain words as animals or objects, or as words or pseudowords by pressing a button with either their left or right hand. This allowed the researchers to use EEG recordings to analyze the participant's lateralized readiness potential (LRP) as they mapped each semantic category with a specific motor movement (e.g., pressing the right button with their right hand for animals). During sleep, participants were then exposed to a new list of words to ensure that LRPs were associated with the extraction of word meanings, rather than just a reactivation of stimulus-response associations. The researchers discovered two negative LRPs peaks, time-locked at around 660 and 1620 ms, which were statistically similar in both awake and sleep conditions. In addition, a positive LRP peak at around 3000 ms was only observed in awake individuals. They suggested that the initial negative LRP peaks were associated with the planning of the motor response, whereas the positive peak in awake individuals was associated with the performance of the motor task. This indicates that the brain can extract task-relevant semantic information and prepare for its associated motor responses during sleep. These results also provide evidence for the semantic categorization of words and higher-level semantic processing occurring in the brain during sleep.

Finally, in a more recent study, Legendre et al. (2019) developed a version of the cocktail party paradigm to understand if the brain can filter and attend to relevant sources of information during sleep. In this cocktail party paradigm, participants were presented with two streams of competing speech, one in each ear, during both wakefulness and sleep. One stream consisted of short one-minute relevant stories, while the other stream consisted of "Jabberwocky" speech—speech that is devoid of meaning but with intact phonological and syntactic properties. The researchers used a technique called stimulus reconstruction, where the EEG response signal is translated into a re-creation of the auditory stimulus, allowing them to identify if one speech stream was attended to more strongly by the brain during both wakefulness and NREM sleep. Based on this measure, participants were significantly more likely to track the relevant, informative stream of speech over the Jabberwocky speech during sleep. This investigation was one of the first of its kind to showcase that the brain can filter and attend to relevant sources of continuous speech during sleep. Nonetheless, it is still unclear *which* specific linguistic features are extracted during sleep and how they may account for the observed effect.

In summary, findings from a few previous studies have highlighted that higher-order semantic processing can during sleep. However, apart from Legendre and colleagues' cocktail party paradigm, previous research has been dominated by specialized paradigms that use single words or isolated sentences with specific target words to assess the varying levels of semantic processing during sleep. As a result, there is still much to be learned about the level of semantic processing of natural, narrative speech occurring during sleep.

1.2.3 Speech Segmentation

While several previous studies have examined auditory and semantic processing of linguistic structures occurring during sleep, there has been very little research on the level of speech segmentation processing occurring during sleep. From studies of wake individuals, we know that there are a variety of segmentation cues that contribute to an individual's ability to segment continuous speech (Sanders & Neville, 2003). For example, Cutler and Butterfield (1992) showed that individuals develop heuristics based on their experience with the general structure of the language. They found that English-speaking participants tend to use the heuristic that strong syllables (full vowels) are most likely to be the initial syllables of lexical words (e.g., nouns, verbs, and adjectives), whereas weak syllables (short, central vowels) are most likely to either be non-initial syllables or initial syllables for grammatical words (e.g., articles, pronouns, and conjunctions). Saffran and colleagues (1996) used an artificial language paradigm to show that participants were able to segment words from continuous speech based solely on the statistical probabilities between syllables, suggesting that statistical information may also contribute to speech segmentation. Finally, Sanders and Neville (2000) demonstrated that adults use a variety of cues to segment words in natural speech, including lexical, syntactical, and stress-pattern cues.

Sanders and Neville (2003) were one of the first to investigate the ERPs associated with speech segmentation. They compared ERPs elicited by word onsets with ERPs elicited by word-medial syllable onsets with equivalent acoustic properties. They found that word onsets elicited a larger N100 amplitude compared to the N100 elicited by word-medial syllable onsets. Next, they tested whether semantic and syntactic information influence speech segmentation by comparing ERPs elicited by word onsets and word-medial syllables in sentences with varying amounts of semantic and syntactic content. They discovered that the word onset ERP components are elicited at similar levels, regardless of the semantic or syntactic content of the linguistic structures, suggesting that the initial parsing of speech may be fast and automatic and does not rely on semantic or syntactic cues. These findings also suggest that the N100 amplitude serves as a useful tool to measure speech segmentation processing in the brain.

In a related study, Sanders et al. (2002) sought to confirm that the increased N100 amplitude elicited by word onsets was a reliable indicator of speech segmentation processing, rather than potentially indexing subtle acoustic characteristics that may correlate with word boundaries. They recorded the ERPs from six nonsense words presented as continuous speech before and after the participants learned the nonsense words through explicit training. The rationale behind this paradigm is that once the participants learned the individual nonsense words, they would be able to segment the continuous speech into its component words. This allowed the researchers to compare the ERPs during the initial exposure block, when the nonsense words were not being segmented, to the ERPs during the final block, when nonsense words are presumed to be segmented, eliminating any potential confounds of acoustic segmentation cues. The results showed that participants who displayed greater levels of word knowledge elicited larger N100 amplitudes to word onsets in the post-training block, as compared to before training. This result rules out any potential influences from acoustic segmentation cues and confirms that the N100 amplitude is an effective measure of speech segmentation.

Directly pertaining to the question of whether speech segmentation occurs during sleep, Makov et al. (2017) are the only investigators (to our knowledge) to examine the level of speech segmentation processing occurring in the sleeping brain. They utilized a concurrent hierarchal tracking approach, in which speech sequences were comprised such that different linguistic structures occurred at distinct frequencies. Two-syllable words were used to form two-word phrases and four-word sentences, such that each structure occurs at different fixed time intervals (i.e., syllable rate 4 Hz; word rate 2 Hz; phrase rate 1 Hz, and sentence rate 0.5 Hz). The authors found that neural tracking of acoustic information during sleep was preserved during sleep, as demonstrated by a similar 4 Hz spectral peak in both wake and sleep. However, neural tracking of higher order linguistic structures, including at the word level, was completely disrupted during sleep, and observed only during wake. At face value, this result suggests that speech segmentation cannot proceed during sleep. However, one limitation of this investigation is that the syllables were presented isochronously and that the speech stimuli in general were highly controlled and artificial, eliminating many of the naturally occurring, subtle auditory cues to word onsets. This may have made it more difficult for the sleeping brain to segment the individual words in the speech signal. In addition, the same stimulus frequencies were maintained between sleep and awake. However, previous investigations have identified a delayed level of semantic processing occurring in the brain during sleep (e.g., Brualla et al., 1998), raising the possibility that the sleeping brain was too slow to track the structures at the selected presentation rates. As a result, further research is required to fully understand if speech segmentation processing may be occurring during sleep at a longer latency.

1.3 Linear Regression as a Method for Understanding Continuous Speech Processing

As described in the previous sections, prior studies on speech processing during sleep have mainly used single syllables, single words, or sentences with prespecified, discrete target words as stimuli. These paradigms lack the rich complexity found in typical, narrative speech and may not adequately capture how the brain processes continuous, natural speech during sleep. Historically, the key challenge or barrier to adopting natural, narrative speech as stimuli has been methodological – that is, determining how to analyze complex time-varying neural responses to the complex multivariate linguistic stimuli within continuous speech (Crosse et al., 2016). Previous literature has tended to focus on using single words or syllables as stimuli in order to leverage the traditional ERP approach for analyzing EEG data. This approach requires the use of brief, discrete, isolated stimuli in order to time-lock the EEG data and compute the ERP over multiple trials (Crosse et al., 2016). However, recently, researchers have been able to overcome this methodological issue by using novel methods of system identification to investigate neural responses to continuous stimuli.

In neuroscience, system identification is the method of mathematically modelling the function that describes how a stimulus feature is mapped onto its neural responses (Marmarelis, 2004). The most straightforward and consistently used method of system identification in neuroscience is to treat the brain as a linear time-invariant system (Crosse et al., 2016). Some of the assumptions of the linear time-invariant model include that neural responses depend on stimulus timing and stimulus contrast separately (Boynton et al., 1996). Neural responses to long stimuli durations can be predicted from neural responses to stimuli of shorter length (Boynton et al., 1996). An additional assumption is that the noise in data is independent of the temporal period and stimulus contrast (Boynton et al., 1996). Previous investigations have been able to demonstrate that the assumptions for this model can be accepted in various cases, allowing for the characterization of the brain by its impulse response (Boynton et al., 1996; Ringach & Shapley, 2004). Researchers have begun to develop various models of system identification, using the linear time-invariant model, to analyze the neural responses to naturalistic stimuli. One promising method involves using the technique of regularized linear (ridge) regression to produce an impulse response estimate to naturalistic stimuli (Lalor et al., 2006). This technique has allowed language researchers to develop response functions that describe the linear relationship between linguistic properties of natural speech to neural responses.

Regularized linear regression involves developing a model called the temporal response function (TRF) (see Figure 3). The TRF can be defined as a filter that describes the brain's linear transformation of a stimulus to its continuous neural response over a series of specific time intervals (Crosse et al., 2016). The weights of the TRF are estimated by minimizing the mean squared error between the actual neural response to the neural response predicted by linear convolution (Crosse et al., 2016). Machens and colleagues (2004) were among the first researchers to utilize regularized linear regression to analyze the transformation of an auditory stimulus to the membrane potential of neurons in the rat auditory cortex. They used *in vivo* whole-cell recordings to quantify changes in membrane potentials of neurons in the primary auditory cortex during the presentation of pure tones (Machens et al., 2004). The predicted linear model was able to account for 11% of the neural response power (Machens et al., 2004). Subsequent research sought to optimize the parameters of the linear model and to apply it to other areas of sensory and cognitive processing (Lalor & Foxe, 2010; Ding & Simon, 2012).

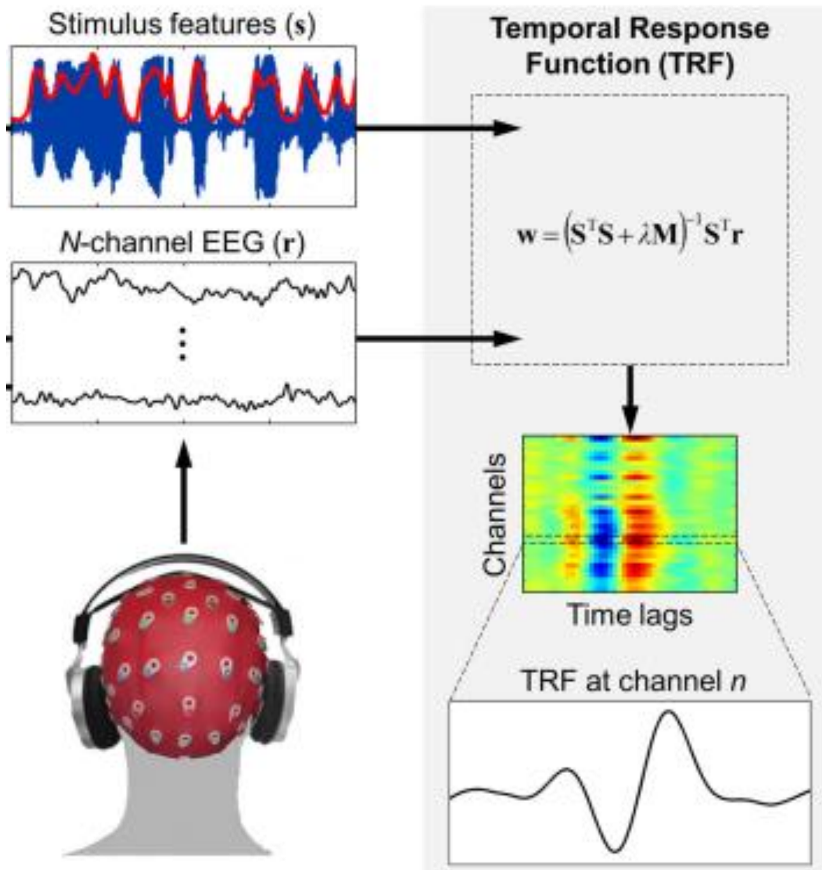

Figure 3. Temporal Response Functions

Schematic of the temporal response function estimation from regularized linear regression (reproduced from Crosse et al., 2016). TRFs are developed by linear mapping of the stimulus features to EEG data and graphed across a series of time lags.

Di Liberto et al. (2015) showed that the neural response to speech can be reliably predicted through a linear transformation model. The authors developed TRFs of EEG data that were recorded as participants listened to segments of an audiobook and compared the linear models developed from analyzing the auditory envelope, phonemes, and phonetic features of the audio segments. They showed that the linear mapping between the continuous speech stimulus and the neural activity was most reliable when a combination of the auditory spectrogram and phonetic features were analyzed, as compared to single individual features such as the auditory envelope. They also found that the linear mapping between phonetic features and EEG becomes stronger at longer latencies (150-200 ms). These results suggest that the regularized linear regression model could represent a useful tool for analyzing and understanding which features of natural, narrative speech are processed during sleep.

Brodbeck et al. (2018) also used a regularized linear regression model to investigate the neurophysiological signals to various linguistic features of speech, including word onsets, providing insights into speech segmentation. They developed a cocktail party paradigm in which auditory segments were extracted from an audiobook read by two different speakers (one male and one female). The researchers combined audio segments from the two speakers and asked participants to attend to a specific speaker as they were exposed to each combined audio segment. They found a TRF peak at 100 ms for word onsets, which closely aligns with the N100 effect reported by previous ERP studies examining speech segmentation (Sander et al., 2002; Sanders & Neville, 2003). The researchers suggested that this tightly locked response to word onsets signifies that the brain detects word boundaries as they occur, rather than incorporating cues occurring before and after the word onset. This evidence also provides support that a TRF component at 100 ms may be used to index the level of speech segmentation occurring during both wake and sleep.

Finally, Broderick et al. (2018) used the mTRF methodology to analyze the neural responses associated with the semantic processing of natural, continuous speech. They recorded EEG data as participants listened to an excerpt from an audiobook, presented both intactly and time reversed. To measure speech comprehension, they used a computational model (word2vec) to quantify the semantic "expectedness" or similarity of each word given its preceding context. The word2vec model operates on the premise that words with similar meanings tend to occur in similar contexts. To quantify the semantic dissimilarity of each word, the researchers used the word2vec model to calculate the Pearson's correlation between each word's vector to the average of the vectors of all preceding words in the same sentence. Next, they developed a TRF that maps the semantic dissimilarity vector to the recorded EEG responses. They discovered a prominent negative TRF component at 200 ms – 600 ms, maximal over centro-parietal channels, sharing many characteristics of the N400 ERP component. This negativity was not observed when time-reversed speech was played. These results suggest that the brain processes the semantic context of each word in relatively time-locked fashion, even in this context of continuous narrative speech. This result also provides further evidence that the mTRF methodology will be useful in analyzing the neural responses of sleeping participants. In addition, the word2vec model will serve as another useful tool for understanding the level of speech comprehension processing occurring in the sleeping brain.

1.4 Present Study

Recently, a team of researchers at the University of Rochester developed an open-source toolbox on MATLAB, called the mTRF toolbox, that implements the regularized linear regression technique to develop TRFs for a variety of stimulus features (Crosse et al., 2016). The toolbox can be used to develop TRFs by training the model on each trial separately and averaging across the weights across all models, or by training the model on multiple trials simultaneously. Furthermore, for each trial, the toolbox can train on all features of the data set simultaneously, if the stimulus vector and the neural response data are equated in timepoints and sampling rate. Crosse and colleagues used this toolbox to characterize the TRF that reliably maps the auditory envelope of a continuous speech stimulus to EEG recordings. They discovered that the auditory envelope evoked TRF components at 50 ms, 80 ms and 140 ms, which were strongest around fronto-central electrodes. We used this toolbox in the current study to implement the regularized linear regression technique for the analysis of linguistic features of natural, narrative speech during sleep.

Expanding on the previous investigations, the present study used regularized linear regression to understand which features of natural, narrative speech are processed during sleep. In this investigation, participants were exposed to a natural speech stimulus from an audio recording of J.D. Salingers' *Pretty Mouth and Green My Eyes* (GME), while they were either in NREM sleep or lying down in the bed awake. They were also exposed to a scrambled version of the audio excerpt that acted as a control for this investigation. The mTRF toolbox was used to develop TRFs that map the relationship between the (1) auditory envelope, (2) word onsets, and (3) semantic dissimilarity of individual words in this natural, narrative speech stream and the EEG neural responses generated by the sleeping brain. Building on the previous findings, we expect that TRFs will exhibit similar waveforms between awake and sleeping participants for low-level acoustic features, providing evidence of preserved low-level auditory processing during sleep (Makov et al., 2017; Portas et al., 2000). We also hypothesized that above-chance levels of speech segmentation and semantic processing compared to a control scrambled speech condition—as indexed by a negativity response at 100 ms (word onsets; Brodbeck et al., 2018) and over the 200-500 ms range (semantic dissimilarity; Broderick et al., 2018)—will occur even during sleep. However, we expect that neural markers of speech segmentation and semantic processing during sleep may be diminished as compared to wake, reflecting compromised higher-level language processing during sleep. This investigation will allow us to understand the linguistic processing capabilities of the sleeping brain, contributing to our overall understanding of levels of conscious awareness during sleep.

Chapter 2

2 Methods

2.1 Ethics Statement

Participants provided informed written consent and ethics approval for the study was provided by the Research Ethics Board at Western University (REB #112576; see Appendices A and B).

2.2 Participants

EEG data that was previously collected as part of a Masters' thesis project and had not yet been analyzed was used for this investigation (Hollywood, 2020). Participants between the ages of 17 to 35 were recruited using Western University's SONA recruiting system and flyers placed around the university campus. Participants were compensated with course credits or $14 per hour. The inclusion criteria required that participants had intact or corrected-to-intact vision; no personal history of speech, hearing, learning, neurological, sleep or psychiatric disorders; intact hearing; and were not taking any medications that could affect intact brain functioning.

The participant sample for the experimental sleep condition was comprised of 17 participants (14 female), ranging from 17 to 30 years old (M = 20.18, SD = 4.12). In addition, data were collected from an additional 11 participants but excluded from the final sample, as four participants were unable to fall asleep during the experimental session, two participants were unable to remain asleep, two participants due to technical issues with EEG acquisition and three participants due to technical issues with stimulus onset tracking. The participant sample for the control condition was comprised of 15 participants (8 female), ranging from 18 to 34 years old (M = 23.47, SD = 5.32). In addition, data was collected from one additional participant but discarded due to technical issues with stimulus onset tracking. Participants in the experimental sleep condition self-reported as being able to nap well during the afternoon. They were asked to wake up 1-2 hours earlier than usual in the morning to facilitate their afternoon nap. They were also asked to refrain from consuming any caffeinated beverages or other stimulants on the day of their participation.

2.3 Apparatus

The Brain Products actiCAP 64-channel standard EEG system was used to record neural activity throughout the experiment. There were four external electrodes placed on the face to monitor eye movement and muscle tone for sleep staging. These electrodes were placed beside each eye, the chin and beside the mouth. The EEG data were sampled at 500 Hz and referenced online to a built-in reference electrode located near Cz, using the Brain Vision software. Electrode impedances were maintained below 20 kΩ.

The auditory stimuli were played through computer speakers that were placed 1.5 m apart on both sides of the bed to ensure binaural audio presentation. Auditory stimuli were presented through a 2018 MacBook Pro using PsychoPy and triggers for the start and stop times of the auditory stimuli were sent to MacBook using the Cedrus StimTracker.

2.4 Materials

There were two pieces of auditory stimuli used in this investigation. The first piece was an interview with a philosopher named John Butler, discussing his life and meditation (see Appendix C). This auditory stimulus was used as a transitory stimulus and was played as the participants were beginning to fall asleep until the participant reached NREM2 sleep. During piloting, some participants reported being startled awake when the main auditory stimulus was played in the quiet environment. This transitory auditory stimulus eased the transition to the presentation of the main auditory stimulus.

The main experimental auditory stimulus was an excerpt from J.D. Salingers' *Pretty Mouth and Green My Eyes* (GME; see Appendix D). This GME excerpt has been shown to elicit consistent neural responses across individuals during wake (Yeshurun et al., 2017). The excerpt involves phone conversation between two men about a possible marital affair, is engaging and suspenseful, and contains a variety of different emotions and voices, which may increase the likelihood that sleeping participants are able to track the story. A scrambled version of the GME excerpt was also used as a control in this investigation by cutting the GME audio waveform into short 25-ms overlapping windows (50% overlap), tapering them with a cosine window and then shuffling them over a ±250-ms window from its original position. This method of scrambling preserves the spectral content of the auditory script over longer time scales but removes its structure at shorter timescales (Ellis & Lee, 2004). The scrambled speech excerpt has similar low-level audio features to intact speech but is not comprehensible. Comparison of the TRF waveforms developed between intact versus scrambled speech allows us to isolate effects of semantic/linguistic content from lower-level effects of stimulus acoustics. Both the intact and scrambled speech streams were just under 7 min in length.

Participants also completed a variety of questionnaires prior to and upon completion of their afternoon nap. Demographic information was collected using the Adult Participant Information sheet before their afternoon nap (see Appendix E). Participants also completed the Sleepiness and Fatigue questionnaire to report how drowsy they felt on a normal day and the Karolinska Sleep Log to report their normal nocturnal sleep habits and their quality and duration of sleep during the night prior to the study relative to a normal night (see Appendices F and G). They also completed the Karolinska Nap Log to report the quality of their nap (see Appendix H).

2.5 Procedure

2.5.1 Experimental Sleep Group

Participants arrived at the Western Interdisciplinary Research Building at Western University (London, ON) for their experimental session sometime between 11am to 2pm. They were asked to read the Letter of Information and provide informed consent. The participants then completed the pre-nap questionnaires. The EEG cap was placed on the participant’s head and electrode impedances were tested and maintained at below 20 kΩ. The volume of the auditory stimuli was adjusted on a subject-by-subject basis to ensure that the stimulus was loud enough to comprehend but would not be loud enough to wake up the participant. They then reclined in a bed located in a dark room and were given the opportunity to sleep for up to 1.5 hours.

The John Butler interview excerpt was played in the background as the participant was falling asleep. Participants' EEG was monitored online by the experimenter. When the participant entered a stable form of NREM2 sleep, the auditory stimulus was switched from the John Butler interview to the main auditory stimulus. The GME excerpt and the scrambled version of the GME excerpt were both played twice after the participant entered NREM2 sleep. The excerpts continued to be played even if the participants transitioned to other stages of sleep (e.g., NREM3, REM), but was paused if participants showed signs of arousal. The order of the conditions was counterbalanced between participants, as half the participants listened to the scrambled version first, while the other half listened to the intact version first. The audio recordings were then played in alternating order (i.e., (1) scrambled, random, scrambled, random, or (2) random, scrambled, random, scrambled). Participants were then allowed to sleep in silence for the rest of the 90-minute nap period and woke up either naturally or by a knock on the door. The EEG cap was removed, and participants could wash off any EEG gel that remained in their hair. The researcher asked the participant probing questions to understand their level of awareness of the stimuli during their nap and the participants were also asked to complete the Karolinska Nap Log (see Appendix I). Upon completion of the questionnaire, the participants were debriefed and compensated for their participation prior to leaving the lab (see Appendix J). The entire experimental session lasted approximately three hours. Three individuals reported hearing the scrambled audio audiobook; however, sleep stage scoring reflected that all individuals remained in NREM sleep throughout the playing of the GME recordings.

2.5.2 Control Awake Group

For the control awake group, participants followed the same experimental procedures as the experimental group up until the nap period began. At this point, they could lay down in a bed located in a dark room but were asked to stay awake during the entire experimental session. The GME excerpt and the scrambled version of the GME excerpt were both played twice while the participant was lying in bed. The order of the auditory stimuli was counterbalanced using the same scheme as described for the sleep group. The EEG cap was removed, and participants could wash off any EEG gel that remained in their hair. The researcher asked the participant probing questions to understand their memory of the stimuli. The participants were debriefed and compensated for their participation prior to leaving the lab. The entire experimental session lasted approximately 1.5 hours.

2.6 EEG Preprocessing

EEG preprocessing was completed using the EEGLAB toolbox in the MATLAB software (Delorme & Makeig, 2004). The EEG channels were band-pass filtered through a 1-8 Hz digital finite impulse response (FIR) bandpass filter with a notch filter at 60 Hz, as recommended by Crosse et al. (2016). The EEG data was down sampled to 100 Hz. Automatic artifact detection was used to flag noisy channels for removal. Noisy channels were identified if their average amplitude variance was at least two standard deviations greater than the mean. The noisy channels were replaced by the interpolated signals from surrounding electrodes and the EEG data was re-referenced offline to the average across the entire head.

2.7 EEG Analyses

2.7.1 Creation of Stimulus Vectors

The auditory envelope of both the GME audio and the scrambled GME audio was extracted using the Music Information Retrieval (MIR) toolbox running through MATLAB (Lartillot et al., 2008). The word onset times were manually coded by two researchers by examining the audio waveforms and listening to the audio excerpt through the Audacity software. The inter-rater reliability between the two raters was 93.2%, based on a threshold difference of 5 ms, and discrepancies were resolved by calculating the mean from the two sets of times. The word onset vector was developed by assigning a value of 1 at each time point corresponding to the time of each word onset. The semantic dissimilarity vector was developed using the word2vec algorithm in the MATLAB software. The fastTextWordEmbedding function in the MATLAB software was used, which was a function that called upon a word2vec model that consisted of 300 dimensional pretrained word embeddings for one million English words (Mikolov et al., 2017). The word2vec function was used to derive 300 dimensional vectors for each word in the GME audiobook. Following the same general procedure as Broderick and colleagues (2018), to quantify the semantic dissimilarity of each word, a Pearson's correlation coefficient was calculated between each word's 300-dimensional vector with the average of the preceding words in the sentence. For words that were the first word in a sentence, the coefficient was calculated between the word's vector with the average of all the word vectors from the preceding sentence. The Pearson correlation coefficients were then subtracted from 1, so that highly semantically similar words had values closer to 0 while highly semantically dissimilar words had values closer to 2. Each coefficient was then assigned as a time-aligned impulse in the semantic dissimilarity vector at the time point corresponding to the onset of the word. All vectors were sampled at 100 Hz and consisted of 41,745 time points, corresponding to the length of the GME audiobook.

2.7.2 Temporal Response Functions

The EEG data were normalized by Z-scoring the EEG data across time points for each channel at the individual level before estimating the TRF (Broderick et al., 2018). TRFs for the auditory envelope vector, the word onset vector and the semantic dissimilarity vector were then developed by training each model across all the trials simultaneously using the mTRF toolbox. This involved computing a channel-specific mapping between each vector and the EEG data. The estimation of the TRF weights was performed through the mTRF toolbox, in which the mean squared error between the actual neural response to the neural response predicted by linear convolution was minimized. Baseline correction was performed on each participant's average TRF at each channel, by subtracting the mean value of -20 ms to 0 ms, prior to calculating the grand average TRF

(Drennan & Lalor, 2019). Topographical distributions of the resulting TRFs over the scalp were visualized through EEGLAB's *topoplot* function (Delorme & Makeig, 2004).

To identify appropriate time windows and electrodes for statistical analysis, we first visually inspected the TRF waveforms for all 63 electrodes. Based on our observations of all electrodes, we selected time bins for statistical analysis that corresponded to peaks in the TRF time course. Based on the scalp topographies of these selected time bins, we then identified the key representative electrode(s) that showed the maximal TRF values for further analysis. TRF waveforms at each key electrode were tested to be significantly greater than or less than zero using a running one-tailed t test across all subjects. The resulting p values were corrected using the False Discovery Rate (FDR) method, correcting for the number of timepoints tested. When relevant to the research question, we also tested whether the topographical distributions of the TRF peaks differed significantly between wake and sleep (or between the intact audiobook and scrambled audiobook conditions) by conducting a repeated-measures ANOVA, with wake/sleep as a between-subjects factor and anterior/posterior [3 levels: anterior, middle, posterior] and laterality [left lateral, midline, right lateral] as within-subjects factors. The 9 electrode quadrants were created by evenly sectioning the electrode montage into a 3 x 3 matrix based on the electrode's location on the EEG cap (see Appendix K; see Table 1).

Anterior/Posterior	Laterality	Electrodes
Anterior	Left Lateral	AF7, F7, F5, F3
Anterior	Midline	Fp1, Fpz, Fp2, AF3, AF4, F1, Fz, F2
Anterior	Right Lateral	AF8, F8, F6, F4
Middle	Left Lateral	FT9, FT7, FC5, FC3, T7, C5, C3, TP9, TP7, CP5, CP3
Middle	Midline	FC1, FC2, C1, Cz, C2, CP1, CPz, CP2
Middle	Right Lateral	FC4, FC8, FT8, FT10, C4, C6, T8, CP4, CP6, TP8. TP10
Posterior	Left Lateral	P7, P5, P3, PO7
Posterior	Midline	P1, Pz, P2, PO3, POz, PO4, O1, Oz, O2
Posterior	Right Lateral	P4, P6, P8, PO8

Table 1. Electrode Regions

The cluster of electrodes at each region analyzed in the ANOVA analyses.

Chapter 3

3 Results

3.1 Auditory Envelope Analysis

3.1.1 Awake vs. Sleep Comparison

We compared the TRFs associated with processing of the auditory speech envelope between awake and sleeping participants. In the wake group, a prominent positivity is apparent over frontal areas of the scalp peaking at around 40-60 ms, whereas this positivity appeared to be delayed in the sleep group, with a peak latency of around 60-80 ms (see Figure 4A). Similarly, a second positive peak was observed across fronto-central areas of the brain peaking from 170-190 ms in the wake group and 220-240 ms in the sleep group (see Figure 4B). Finally, there was a strong negativity localized across posterior and central regions of the brain peaking at around 260-280 ms in the awake participants. Similarly, there was a strong negativity exhibited by sleeping participants at around 360-380 ms, however, this negativity was localized around fronto-central regions of the brain (see Figure 4C).

These observed peaks were tested statistically. In awake participants, capturing the first peak, awake participants displayed significant positive TRF components across 0-60 ms at the Fz electrode (Figure 4A). The second TRF component among the awake participants at around 170-190 ms was not significant (Figure 4B). For the third peak, awake participants showed a significant negativity from 200-340 ms at the Cz electrode ($p < .05$, FDR corrected; Figure 4C). In contrast, the first two components in sleeping participants were not significant (Figure 4A & B). For the third component, sleeping participants showed a significant negative effect from 310-400 ms at the FC1 electrodes ($p < .05$, FDR corrected; Figure 4C).

Next, we examined whether the distribution of the three TRF components differed between the two groups. For the first positive peak observed at 40-60s in awake participants and 60-80 ms in sleeping participants, Mauchly's test of sphericity was significant for both the anterior vs. posterior factor, $X^2(2) = 26.78$, $p < .001$ and the laterality factor, $X^2(2) = 6.72$, $p = .035$, thus sphericity was not assumed for both factors. Across both groups, the first positive TRF peak (40-60 ms in wake; 60-80 ms in sleep) was relatively widespread, showing no significant differences along the anterior/posterior axis (Anterior versus Posterior factor: $F(2,30) = .534$, $p = .471$), nor from left to right across the scalp (Laterality factor: $F(2,30) = .282$, $p = .714$). Importantly, the distribution of the TRFs did not differ significantly between the sleep and wake groups (Condition x Anterior vs. Posterior Factor: ($F(2,30) = 2.47$, $p = .116$; Condition x Laterality: $F(2,30) = .375$, $p = .667$; Condition x Anterior vs. Posterior Factor x Laterality: $F(4,30) = 1.52$, $p = .215$).

For the second positive peak observed at 170-190 ms in awake participants and 220-240 ms in sleeping participants, Mauchly's test of sphericity was significant for both the anterior vs. posterior factor, $X^2(2) = 25.43$, $p < .001$ and the laterality factor, $X^2(2) = 5.89$, $p = .053$, thus sphericity was not assumed for both factors. Across both groups, the positive peak was not significantly different from anterior to posterior regions across the scalp (Anterior versus Posterior factor: $F(2,30) = .148$, $p = .774$), as well as from left to right across the scalp (Laterality factor: $F(2,30) = .889$, $p = .402$). The distribution of the TRFs differed significantly between the sleep and wake groups, as awake participants elicited a stronger positivity across frontal regions of the brain while sleeping participants elicited a stronger positivity across central regions of the brain (Condition x Anterior vs. Posterior Factor: ($F(2,30) = 6.52$, $p = .009$; Condition x Laterality: $F(2,30) = 1.02$, $p = .357$; Condition x Anterior vs. Posterior Factor x Laterality: $F(4,30) = .379$, $p = .705$).

Finally, for the third negative peak observed at 260-280 ms in awake participants and 360-380 ms in sleeping participants, Mauchly's test of sphericity was significant for the anterior vs. posterior factor, $X^2(2) = 9.705$, $p = .008$ and non-significant for the laterality factor, $X^2(2) = .460$, $p = .794$. Thus, sphericity was assumed for the laterality factor and not assumed for the anterior vs. posterior factor. The distribution of the TRFs differed significantly between the sleep and wake groups, as awake participants showed a stronger negativity across more posterior regions of the brain while sleeping participants showed a stronger negativity across more frontal regions of the brain (Condition x Anterior vs. Posterior Factor: (F(2,30) = 4.23 p = .029; Condition x Laterality: F(2,30) = .336, p = .716; Condition x Anterior vs. Posterior Factor x Laterality: F(4,30) = .660, p = .522).

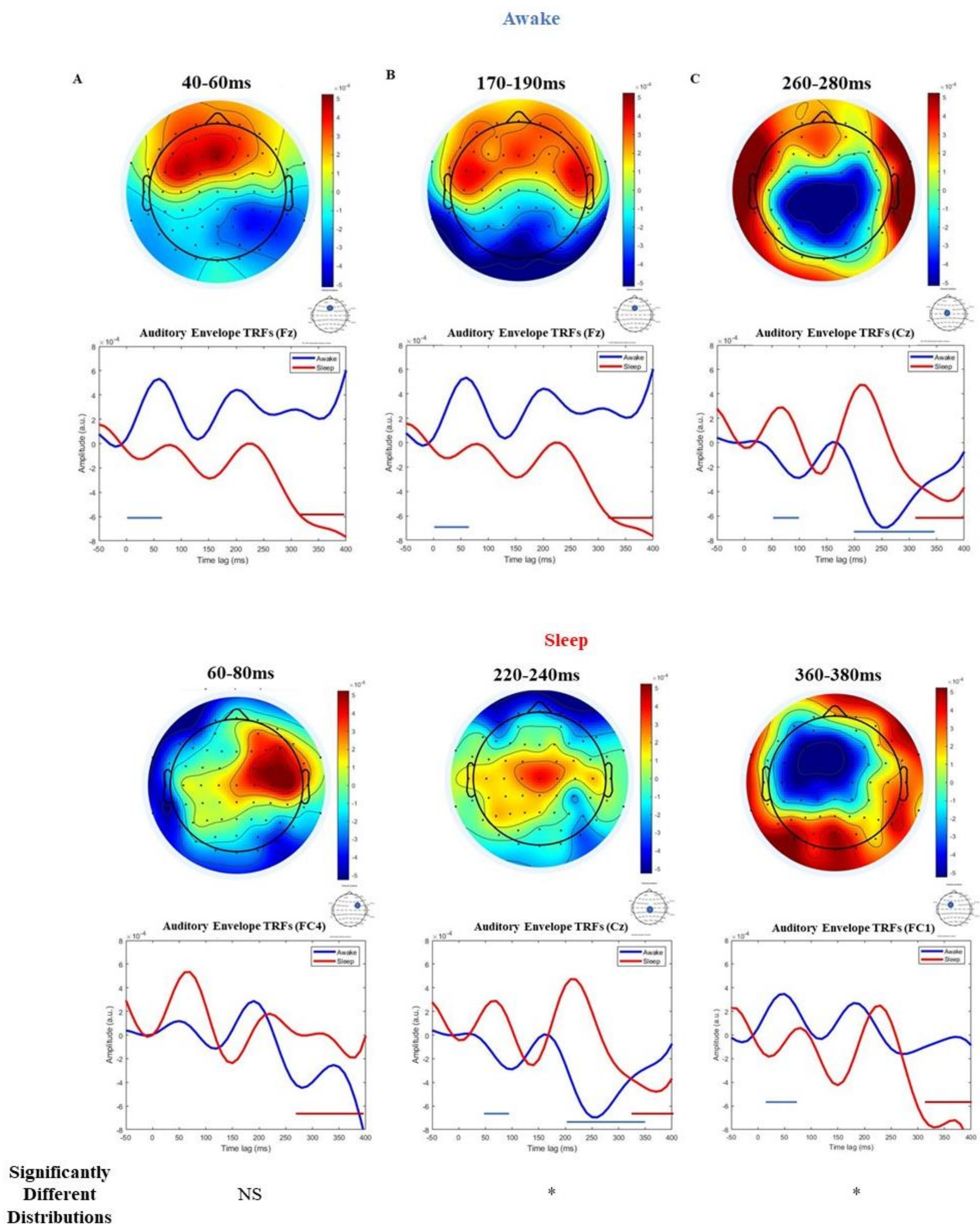

Figure 4. Auditory Envelope TRFs Between Sleep and Awake Participants

A. The topographical distributions of auditory envelope TRF peak at 40-60 ms for awake participants and 60-80 ms for sleeping participants. There was no significant difference between the two topographical distributions. The TRFs developed from the linear regression of the auditory envelope vector with neural EEG responses in both asleep and awake participants at the Fz and FC4 electrodes. Significant TRF components for awake participants are indicated with blue bars and significant TRF components for sleeping participants are indicated with red bars ($p < .05$, FDR corrected). **B**. The topographical distributions of auditory envelope TRF peak at 170-190 ms for awake participants and 220-240 ms for sleeping participants. The positivity is localized in anterior and central regions of the brain and there was a significant difference between the two topographical distributions. The TRFs developed from the linear regression of the auditory envelope vector with neural EEG responses in both asleep and awake participants at the Fz and Cz electrodes. Significant TRF components for awake participants are indicated with blue bars and significant TRF components for sleeping participants are indicated with red bars ($p < .05$, FDR corrected). **C**. The topographical distributions of auditory envelope TRF peak at 260-280 ms for awake participants and 360-380 ms for sleeping participants. There was a significant difference between the localization of the negativity across the brain. The TRFs developed from the linear regression of the auditory envelope vector with neural EEG responses in both asleep and awake participants at the Cz and FC1 electrodes. Significant TRF components for awake participants are indicated with blue bars and significant TRF components for sleeping participants are indicated with red bars ($p < .05$, FDR corrected).

Next, the TRFs developed by linearly regressing the auditory envelope of the scrambled version of the GME audiobook to the EEG data collected from awake and sleep participants were compared. In the wake group, a prominent positivity is apparent over frontal areas of the scalp at around 50-80 ms, whereas a much later positivity with a different topographical distribution was observed in the sleep group at around 200-220 ms (see Figure 5A).

Statistically, awake participants displayed a significant positive TRF component at around 20-100 ms at the FC1 electrode ($p < .05$, FDR corrected; see Figure 5B). However, in sleeping participants, the prominent positive TRF component elicited at around 200-250 ms was not significantly different from zero ($p < .05$, FDR corrected; see Figure 5B).

Mauchly’s test of sphericity was significant for the anterior vs. posterior factor, $X^2(2) = 33.82$, $p < .001$ and non-significant for the laterality factor, $X^2(2) = .920$, $p = .631$. Thus, sphericity was assumed for the laterality factor and not assumed for the anterior vs. posterior factor. Across both groups, the positive TRF peak (50-80 ms in wake; 200-220 ms in sleep) showed a similar distribution anterior to posterior across the scalp (Anterior versus Posterior factor: $F(2,28) = 1.857$, $p = .180$), while showing a similar distribution from left to right across the scalp (Laterality factor: $F(2,28) = .309$, $p = .735$). Importantly, the distribution of the TRFs did not differ significantly between the sleep and wake groups (Condition x Anterior vs. Posterior Factor: ($F(2,28) = .378$, $p = .578$; Condition x Laterality: $F(2,28) = .043$, $p = .958$; Condition x Anterior vs. Posterior Factor x Laterality: $F(4,28) = .368$, $p = .754$).

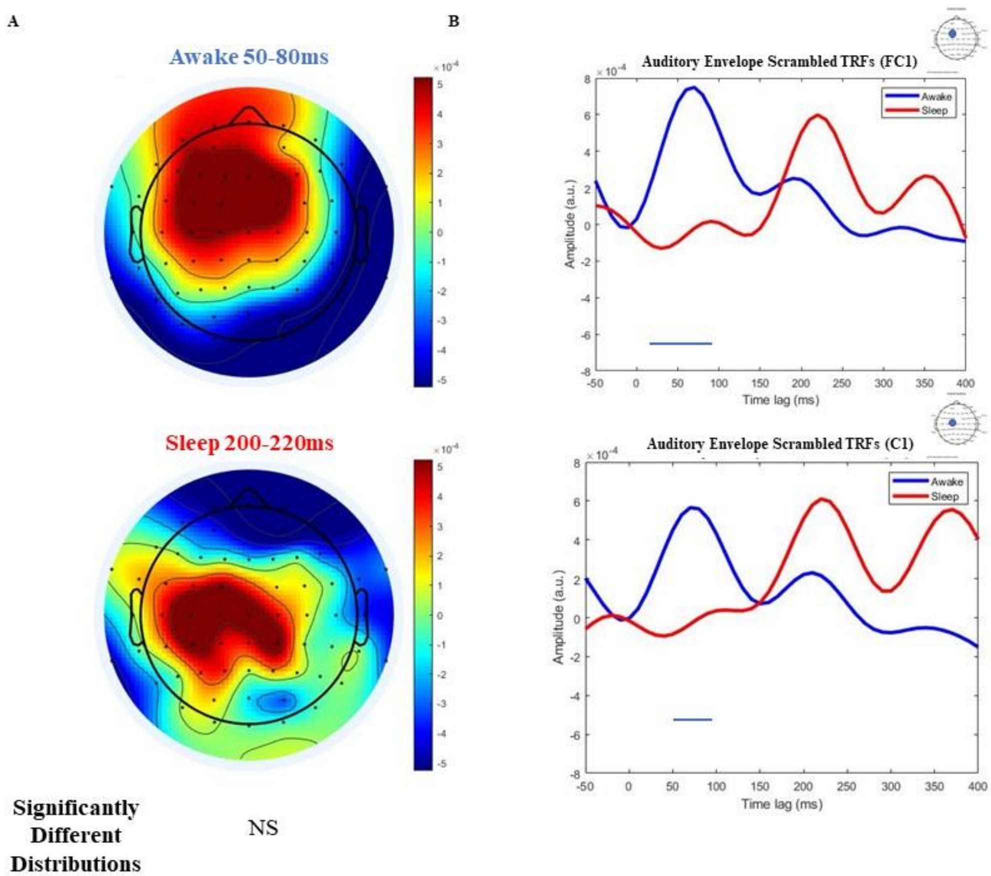

Figure 5. Scrambled Auditory Envelope TRFs Between Sleep and Awake Participants

A. The topographical distributions of the scrambled auditory envelope TRF peak at 50-80 ms for awake participants and 200-220 ms for sleeping participants. There was no significant difference between the two topographical distributions. **B**. The TRFs developed from the linear regression of the scrambled auditory envelope vector with neural EEG responses in both asleep and awake participants at the FC1 and C1 electrodes. Significant TRF components for awake participants are indicated with blue bars ($p < .05$, FDR corrected).

3.1.2 Intact vs. Scrambled Speech Direct Comparison

Interestingly, in awake participants, a prominent TRF component elicited by the scrambled audiobook version was observed, which showed some similar characteristics to the first positive TRF component elicited by the intact version of the audiobook (see Figure 6A). For the intact audiobook version, a significant positive TRF components was found from 10-60 ms. In the scrambled condition, a significant positive TRF component was found from 20-100 ms at the FC1 electrode ($p < .05$, FDR corrected; see Figure 6B).

Mauchly's test of sphericity was significant for the anterior vs. posterior factor, $X^2(2) = 37.38$, $p < .001$ and non-significant for the laterality factor, $X^2(2) = .964$, $p = .618$. Thus, sphericity was assumed for the laterality factor and not assumed for the anterior vs. posterior factor. Across both conditions, the positive TRF peak (40-60 ms in intact; 50-80 ms in scrambled) showed a similar distribution anterior to posterior (Anterior versus Posterior factor: $F(2,30) = 1.082$ $p = .319$), as well as left to right across the scalp (Laterality factor: $F(2,30) = 2.67$, $p = .113$). However, the distributions of the TRFs did differ significantly between the intact and scrambled conditions as individuals listening to the scrambled condition elicited a stronger positivity that spanned both frontal and central regions of the brain, whereas the positivity elicited by individuals listening to the intact condition of the GME audiobook was localized primarily in frontal regions of the scalp. (Condition x Anterior vs. Posterior Factor: ($F(2,30) = 5.52$, $p = .020$; Condition x Laterality: $F(2,30) = .109$, $p = .897$; Condition x Anterior vs. Posterior Factor x Laterality: $F(4,30) = .748$, $p = .528$).

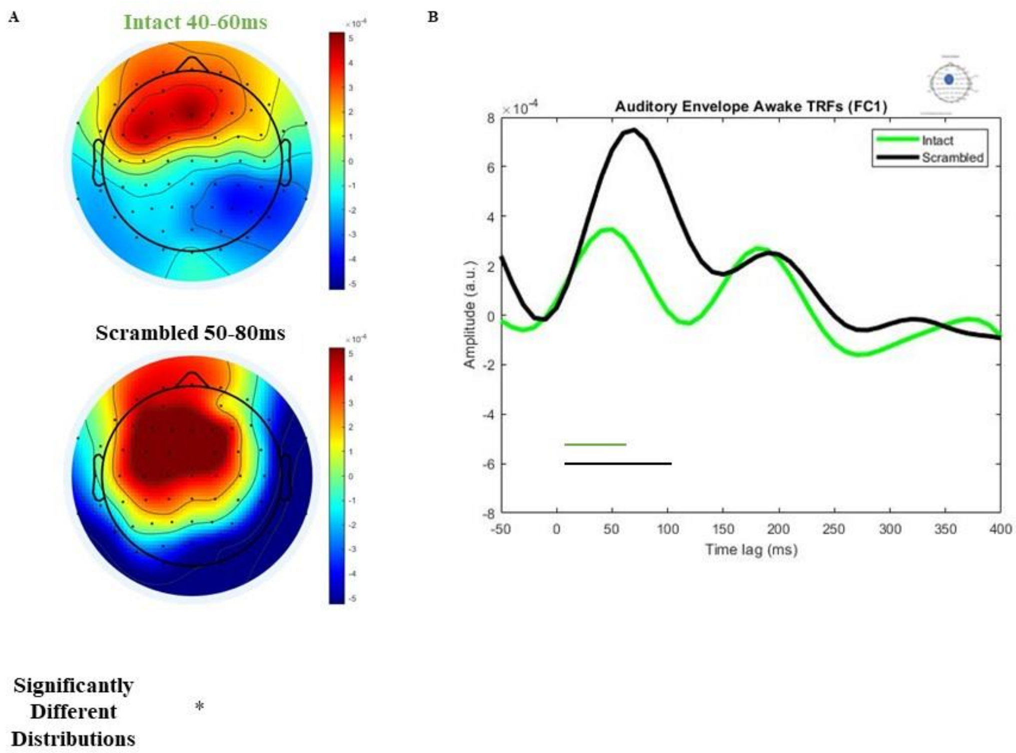

Figure 6. Awake Auditory Envelope TRFs Between Intact and Scrambled Conditions

A. The topographical distributions of the intact auditory envelope TRF peak at 40-60 ms and the scrambled auditory envelope TRF peak at 50-80 ms for awake participants. There was a significant difference between the two topographical distributions. **B**. The TRFs developed from the linear regression of the intact and scrambled auditory envelope vector with neural EEG responses in awake participants at the FC1 electrode. Significant TRF components for the intact condition are indicated with a green bar, while significant TRF components for the scrambled condition are indicated with a black bar ($p < .05$, FDR corrected).

Finally, we compared the TRFs collected from sleeping participants listening to the intact and scrambled versions of the GME audiobook. In the intact condition, a prominent positivity is localized over right frontal areas of the scalp at around 60-80 ms. In the scrambled condition, a prominent positivity was also found, but at a delayed latency, approximately 200-220 ms, and localized to left posterior regions of the scalp (see Figure 7A). Similarly, a second negative peak was observed across fronto-central areas of the brain from 140-160 ms in the intact condition and 290-310 ms in the scrambled condition (see Figure 7B). Finally, there was a strong positivity localized across posterior and central regions of the brain at around 220-240 ms in the intact condition and 360-380 ms in the scrambled condition (see Figure 7C). Thus, qualitatively, there was a similar progression of TRF positivities and negativities to intact and scrambled speech. However, *none* of the TRF components elicited by the sleeping participants were significantly different from zero (see Figure 7D; $p < .05$, FDR corrected).

Mauchly's test of sphericity was significant for the anterior vs. posterior factor, $X^2(2) = 30.03$, $p < .001$ and non-significant for the laterality factor, $X^2(2) = .457$, $p = .796$. Thus, sphericity was assumed for the laterality factor and not assumed for the anterior vs. posterior factor. Across both groups, the first positive TRF peak (60-80 ms in the intact condition; 200-220 ms in scrambled) shared a similar distribution anterior to posterior across the scalp (Anterior versus Posterior factor: $F(2,32) = 1.266$, $p = .279$), while showing a similar distribution from left to right across the scalp (Laterality factor: $F(2,32) = .067$, $p = .935$). Importantly, the distribution of the TRFs did not differ significantly between the intact and scrambled conditions (Condition x Anterior vs. Posterior Factor: ($F(2,32) = .329$, $p = .627$; Condition x Laterality: $F(2,32) = .051$, $p = .950$; Condition x Anterior vs. Posterior Factor x Laterality: $F(4,32) = 1.13$, $p = .338$).

Similarly, for the negative TRF component, Mauchly's test of sphericity was significant for the anterior vs. posterior factor, $X^2(2) = 24.96$, $p < .001$ and non-significant for the laterality factor, $X^2(2) = .529$, $p = .767$. Thus, sphericity was assumed for the laterality factor and not assumed for the anterior vs. posterior factor. Across both groups, the second negative TRF peak (140-160 ms in the intact condition; 290-310 ms in scrambled) was localized in anterior regions of the scalp (Anterior versus Posterior factor: $F(2,32) = 5.59$, $p = .014$), while showing a similar distribution from left to right across the scalp (Laterality factor: $F(2,32) = 1.64$, $p = .203$). Importantly, the distribution of the TRFs did not differ significantly between the intact and scrambled conditions (Condition x Anterior vs. Posterior Factor: ($F(2,32) = .821$, $p = .405$; Condition x Laterality: $F(2,32) = .156$, $p = .856$; Condition x Anterior vs. Posterior Factor x Laterality: $F(4,32) = .647$, $p = .565$).

Finally, for the last positive TRF component, Mauchly's test of sphericity was significant for the anterior vs. posterior factor, $X^2(2) = 16.66$, $p < .001$ and non-significant for the laterality factor, $X^2(2) = 1.19$, $p = .552$. Thus, sphericity was assumed for the laterality factor and not assumed for the anterior vs. posterior factor. Across both groups, the last positive TRF peak (220-240 ms in the intact condition; 360-380 ms in scrambled) was localized in central regions of the scalp (Anterior versus Posterior factor: $F(2,32) = 7.40$, $p = .004$), while showing a similar distribution from left to right across the scalp (Laterality factor: $F(2,32) = .682$, $p = .509$). Importantly, the distribution of the TRFs did not differ significantly between the intact and scrambled conditions (Condition x Anterior vs. Posterior Factor: ($F(2,32) = .339$, $p = .653$; Condition x Laterality: $F(2,32) = .125$, $p = .883$; Condition x Anterior vs. Posterior Factor x Laterality: $F(4,32) = .396$, $p = .742$).

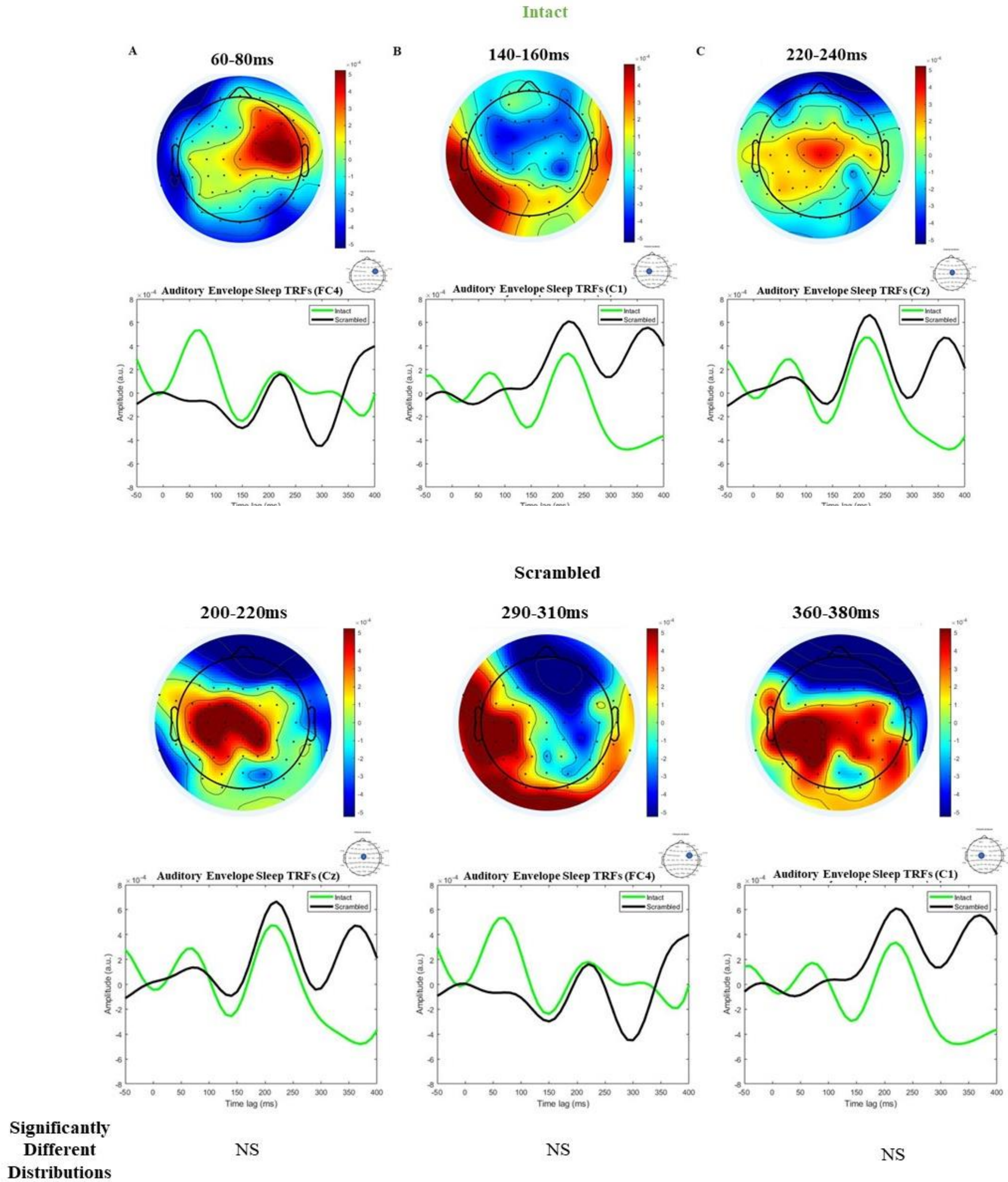

Figure 7. Sleep Auditory Envelope TRFs Between Intact and Scrambled Conditions

A. The topographical distributions of auditory envelope TRF peak at 60-80 ms for the intact condition and 200-220 ms for the scrambled condition. There was no significant difference between the two topographical distributions. The TRFs developed from the linear regression of the intact and scrambled auditory envelope vector with neural EEG responses in sleeping participants at the FC4 and Cz electrode. Significant TRF components for the intact condition are indicated with a green bar ($p < .05$, FDR corrected). **B**. The topographical distributions of auditory envelope TRF peak at 140-160 ms for the intact condition and 290-310 ms for the scrambled condition. There was no significant difference between the two topographical distributions. The TRFs developed from the linear regression of the intact and scrambled auditory envelope vector with neural EEG responses in sleeping participants at the C1 and FC4 electrode. Significant TRF components for the intact condition are indicated with a green bar ($p < .05$, FDR corrected). **C**. The topographical distributions of auditory envelope TRF peak at 220-240 ms for the intact condition and 360-380 ms for the scrambled condition. There was no significant difference between the two topographical distributions. The TRFs developed from the linear regression of the intact and scrambled auditory envelope vector with neural EEG responses in sleeping participants at the Cz and C1 electrode. Significant TRF components for the intact condition are indicated with a green bar ($p < .05$, FDR corrected).

3.2 Word Onset Analysis

3.2.1 Awake vs. Sleep Comparison

Next, we compared the TRFs associated with word onset processing between awake and sleeping participants. Previous investigations identified the 100 ms time lag as a potential time of interest for TRF peaks associated with speech segmentation (Brodbeck et al., 2018). In the wake group a prominent positivity was localized over left frontal areas of the scalp at around 90-110 ms, whereas a similar positivity appeared to be substantially delayed in the sleep group, with a latency of around 240-260 ms in frontal regions of the scalp (see Figure 8A). Similarly, a negativity was observed across central and posterior areas of the scalp from 340-390 ms in the wake group and 380-480 ms in the sleeping group (see Figure 8B).

Statistically, for the awake participants, a significant positive TRF component was observed from 40-280 ms at the C3 electrode, and an additional significant negative TRF component was observed from 340-390 ms at the C4 electrode (see Figure 8A; $p < .05$, FDR corrected). Meanwhile, in sleeping participants, a significant positive TRF component was identified at 210-260 ms for the CP1 electrode ($p < .05$, FDR corrected).

In addition, a significant negative TRF component was observed at 380-500 ms at the C4 electrode (see Figure 8B; $p < .05$, FDR corrected).

For the first positive TRF component (90-110 ms in wake; 240-260 ms in sleep), Mauchly's test of sphericity was significant for both the anterior vs. posterior factor, $X^2(2) = 65.66$, $p < .001$ and the laterality factor, $X^2(2) = 15.14$, $p < .001$, thus sphericity was not assumed for both factors. Across both groups, the first positive TRF peak showed a similar distribution anterior to posterior across the scalp (Anterior versus Posterior factor: $F(2,30) = .183$, $p = .695$), while displaying a strong lateralization in activity to the left side of the brain (Laterality factor: $F(2,30) = 4.055$, $p = .034$). Importantly, the distribution of the TRFs did not differ significantly between the sleep and wake groups (Condition x Anterior vs. Posterior Factor: ($F(2,30) = .467$, $p = .512$; Condition x Laterality: $F(2,30) = 1.011$, $p = .353$; Condition x Anterior vs. Posterior Factor x Laterality: $F(4,30) = .180$, $p = .931$).

For the late negative TRF components, Mauchly's test of sphericity was significant for the anterior vs. posterior factor, $X^2(2) = 33.3$, $p < .001$ and non-significant for the laterality factor, $X^2(2) = .069$, $p = .966$. Thus, sphericity was assumed for the laterality factor and not assumed for the anterior vs. posterior factor. Across both groups, the second negative TRF peak (340-390 ms in the awake condition; 380-480 ms in scrambled) shared a similar distribution anterior to posterior across the scalp (Anterior versus Posterior factor: $F(2,30) = .485$, $p = .532$), while showing a strong lateralization to the midline of the scalp (Laterality factor: $F(2,30) = 3.72$, $p = .030$). Importantly, the distribution of the TRFs did not differ significantly between the sleep and wake conditions (Condition x Anterior vs. Posterior Factor: ($F(2,30) = 1.43$, $p = .246$; Condition x Laterality: $F(2,30) = .922$, $p = .403$; Condition x Anterior vs. Posterior Factor x Laterality: $F(4,30) = .701$, $p = .557$).

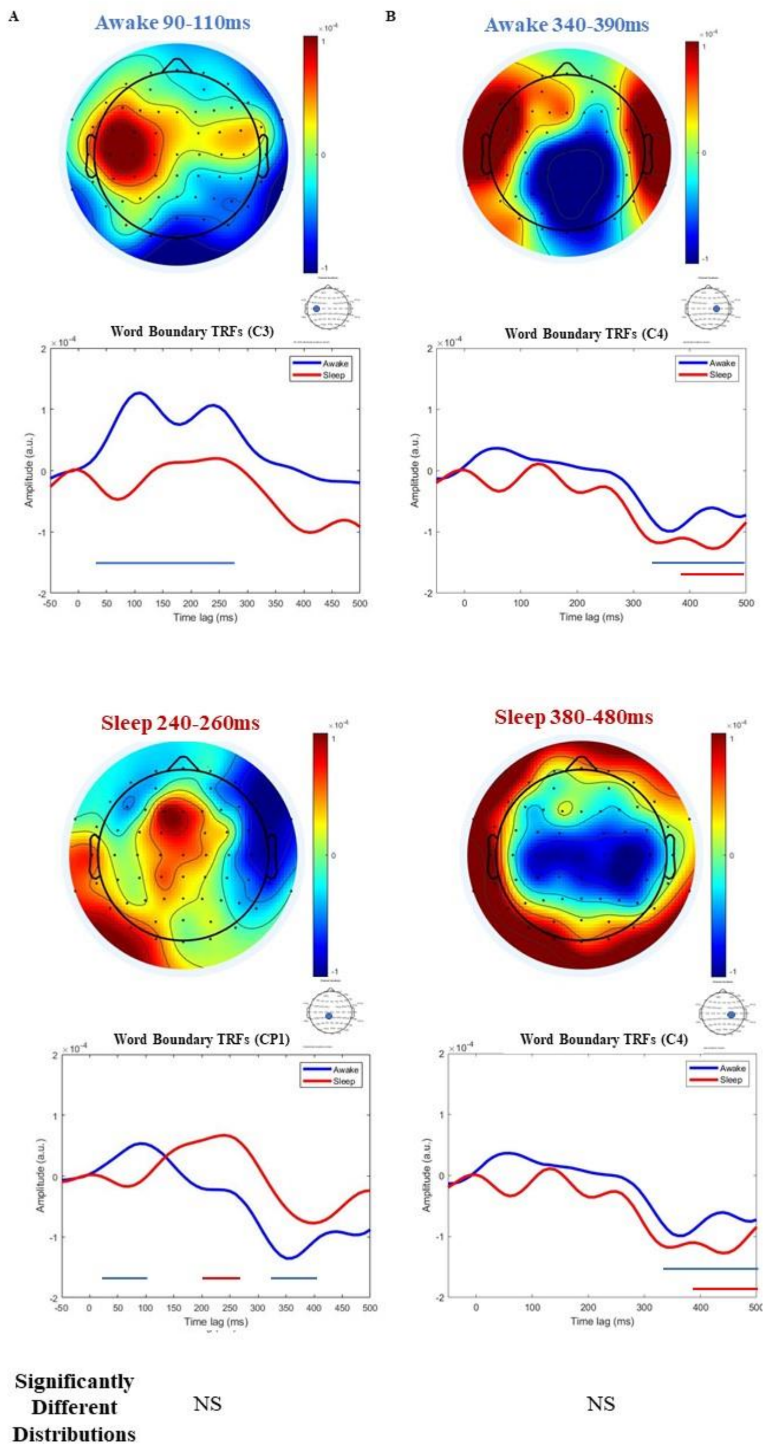

Figure 8. Word Onset TRFs Between Sleep and Awake Participants

A. The topographical distributions of the word onset TRF peak at 90-110 ms for awake participants and 240-260 ms for sleeping participants. There was no significant difference between the two topographical distributions. The TRFs developed from the linear regression of the word onset vector with neural EEG responses in both asleep and awake participants at the CP3 and CP1 electrodes. Significant TRF components for awake participants are indicated with blue bar and significant TRF components for sleeping participants are indicated with a red bar ($p < .05$, FDR corrected). **B**. The topographical distributions of the word onset TRF peak at 340-390 ms for awake participants and 380-480 ms for sleeping participants. There was no significant difference between the two topographical distributions. The TRFs developed from the linear regression of the word onset vector with neural EEG responses in both asleep and awake participants at the C4 electrodes. Significant TRF components for awake participants are indicated with blue bar and significant TRF components for sleeping participants are indicated with a red bar ($p < .05$, FDR corrected).

3.2.2 Intact vs. Scrambled Comparison

The next analysis aimed to compare the TRFs developed by linearly regressing the word boundary vector of the GME audiobook to the EEG data collected from awake participants as they listened to the intact and scrambled versions of the GME audiobook. Critically, no significant peaks were observed in the scrambled version, as indicated by a running t-test against zero. In addition, the significant positive peak at 90-110 ms and the significant negative peak at 340-390 ms in the intact speech condition significantly exceeded the TRF values from the scrambled version ($p < 0.05$, FDR corrected; Figure 9C). These results demonstrate that the peaks observed to word onsets in intact speech is specific to processing of natural, comprehensible speech and not to acoustic stimuli that have similar low-level acoustic features.

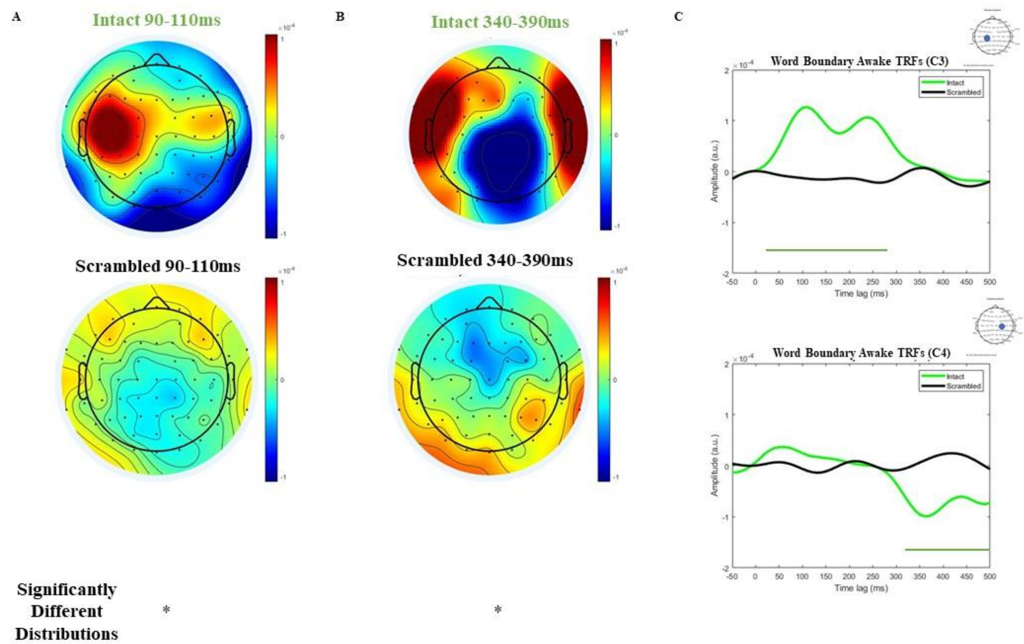

Figure 9. Awake Word Onset TRFs Between Intact and Scrambled Conditions

A. The topographical distributions of the intact word onset TRF peak at 90-110 ms and the scrambled word onset TRF peak at 90-110 ms for awake participants. There was a significant difference between the two topographical distributions. **B**. The topographical distributions of the intact word onset TRF peak at 340-390 ms and the scrambled word onset TRF peak at 340-390 ms for awake participants. There was a significant difference between the two topographical distributions. **C**. The TRFs developed from the linear regression of the intact and scrambled word onset vector with neural EEG responses in awake participants at C3 and C4 electrodes. Significant TRF components for the intact condition are indicated with a green bar ($p < .05$, FDR corrected).

Next, the TRFs developed by linearly regressing the word boundary vector of the GME audiobook to the EEG data collected from sleeping participants as they listened to the intact and scrambled versions of the GME audiobook was compared. At the CP1 electrode, a positive TRF component significantly greater than zero was observed at 210-260 ms for the intact condition, and no TRF component significantly greater than zero was observed for the scrambled condition (see Figure 10C; $p < .05$, FDR corrected). In contrast, a significant negative TRF component was observed from 380-500 ms for the intact condition and a significant *positive* TRF component was observed from 300-480 ms in the scrambled condition at the C4 electrode (see Figure 10C; $p < .05$, FDR corrected).

The topographical distributions of the TRFs were compared between the intact and scrambled conditions in sleeping participants at the time points of the significant TRF peaks in the intact condition (240-260 ms and 380-480 ms; see Figures 10A and 10B). Mauchly's test of sphericity was significant for the anterior vs. posterior factor, $X^2(2) = 50.23$, $p < .001$ and non-significant for the laterality factor, $X^2(2) = 3.71$, $p = .156$. Thus, sphericity was assumed for the laterality factor and not assumed for the anterior vs. posterior factor. Across both groups, the first positive TRF peak (240-260 ms) shared a similar distribution anterior to posterior across the scalp (Anterior versus Posterior factor: $F(2,32) = .675$, $p = .431$), while showing a similar distribution from left to right across the scalp (Laterality factor: $F(2,32) = 1.409$, $p = .252$). Importantly, the distribution of the TRFs did not differ significantly between intact and scrambled conditions (Condition x Anterior vs. Posterior Factor: ($F(2,32) = 1.511$ $p = .230$; Condition x Laterality: $F(2,32) = 1.026$, $p = .363$; Condition x Anterior vs. Posterior Factor x Laterality: $F(4,32) = .432$, $p = .766$).

Similarly, for the peak at 380-480 ms, Mauchly's test of sphericity was significant for the anterior vs. posterior factor, $X^2(2) = 35.43$, $p < .001$, and non-significant for the laterality factor, $X^2(2) = 2.75$, $p = .253$. Thus, sphericity was assumed for the laterality factor and not assumed for the anterior vs. posterior factor. Across both groups, the TRF component (380-480 ms) shared a similar distribution anterior to posterior across the scalp (Anterior versus Posterior factor: $F(2,32) = .503$, $p = .522$), while showing a similar distribution from left to right across the scalp (Laterality factor: $F(2,32) = .747$, $p = .478$). Importantly, the distribution of the TRFs did not differ significantly between the intact and scrambled conditions (Condition x Anterior vs. Posterior Factor: ($F(2,32) = 2.25$, $p = .136$; Condition x Laterality: $F(2,32) = .068$, $p = .935$; Condition x Anterior vs. Posterior Factor x Laterality: $F(4,32) = 1.86$, $p = .138$). We also decided to compare the regions of interest for the significant TRF components at 380-500 ms for the intact condition and 300-480 ms for the scrambled condition at the C4 electrode. There was a significant main effect for the condition ($F(1,32) = 5.95$, $p = .027$), indicating that the TRF components were statistically different from one another.

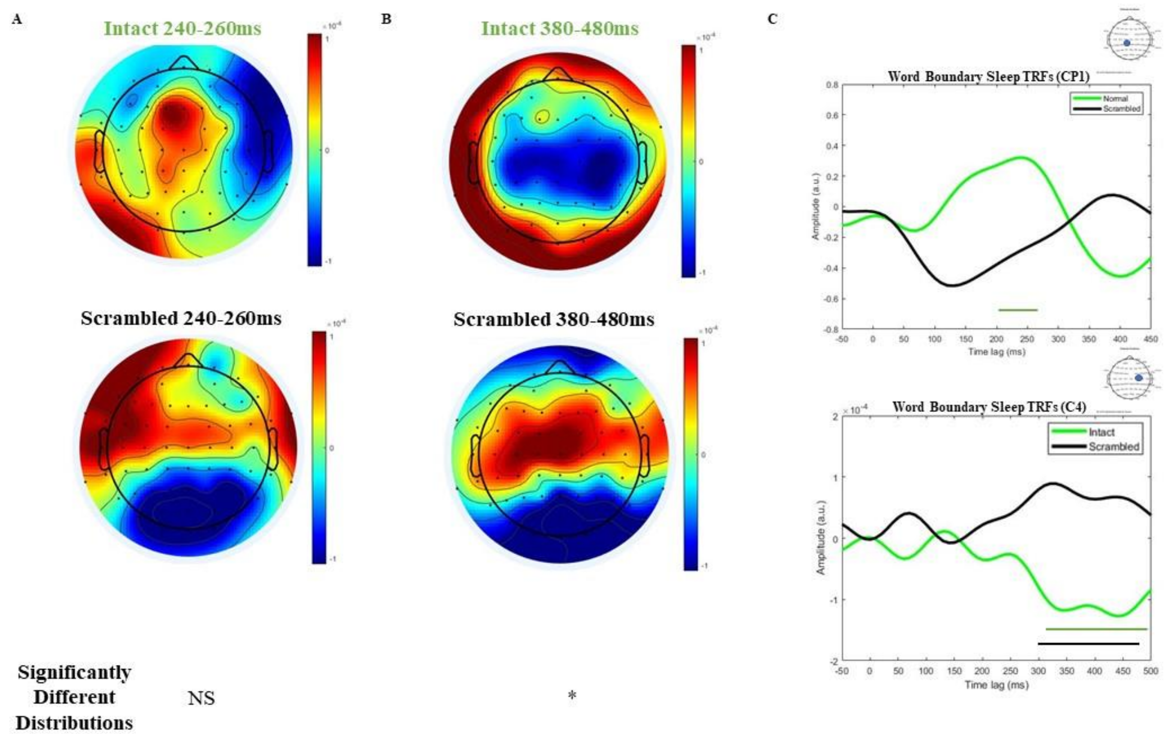

Figure 10. Sleep Word Onset TRFs Between Intact and Scrambled Conditions

A. The topographical distributions of the word onset TRF peak at 240-260 ms for the intact condition and 240-260 ms for the scrambled condition. There was no significant difference between the two topographical distributions. **B**. The topographical distributions of the word onset TRF peak at 380-480 ms for the intact condition and 380-480 ms for the scrambled condition. There was a significant difference between the two peaks **C**. The TRFs developed from the linear regression of the intact and scrambled word onset vector with neural EEG responses in sleeping participants at the CP1 and C4 electrodes. Significant TRF components for the intact condition are indicated with a green bar ($p < .05$, FDR corrected)

3.3 Semantic Dissimilarity Analysis

3.3.1 Awake vs. Sleep Comparison

The TRFs associated with semantic dissimilarity between awake and sleep participants were compared. For awake participants, there was a prominent TRF negativity observed over central and posterior regions of the scalp peaking at around 300-400 ms, while a similar negativity appeared to be delayed with a peak at around 380-480 ms for sleeping participants (see Figure 11A). Statistically, for awake participants, a significant negative TRF component was observed from 290-390 ms at the P2 electrode (see Figure 11B; $p < .05$, FDR corrected). Meanwhile, for sleeping participants, a significant negative TRF component was identified at 430-500 ms at the C4 electrode ($p < .05$, FDR corrected).

Mauchly's test of sphericity was significant for the anterior vs. posterior factor, $X^2(2) = 35.39$, $p < .001$, and non-significant for the laterality factor, $X^2(2) = .081$, $p = .960$. Thus, sphericity was assumed for the laterality factor and not assumed for the anterior vs. posterior factor. Across both groups, the negative TRF component showed a similar distribution from anterior to posterior and from left to right across the scalp (Anterior versus Posterior factor: $F(2,30) = .116$, $p = .890$; Laterality factor: $F(2,30) = 2.86$, $p = .065$). Importantly, the distribution of the TRFs did not differ significantly between wake and sleep (Condition x Anterior vs. Posterior Factor: ($F(2,30) = 1.53$, $p = .228$; Condition x Laterality: $F(2,30) = .565$, $p = .571$; Condition x Anterior vs. Posterior Factor x Laterality: $F(4,30) = .540$, $p = .642$).

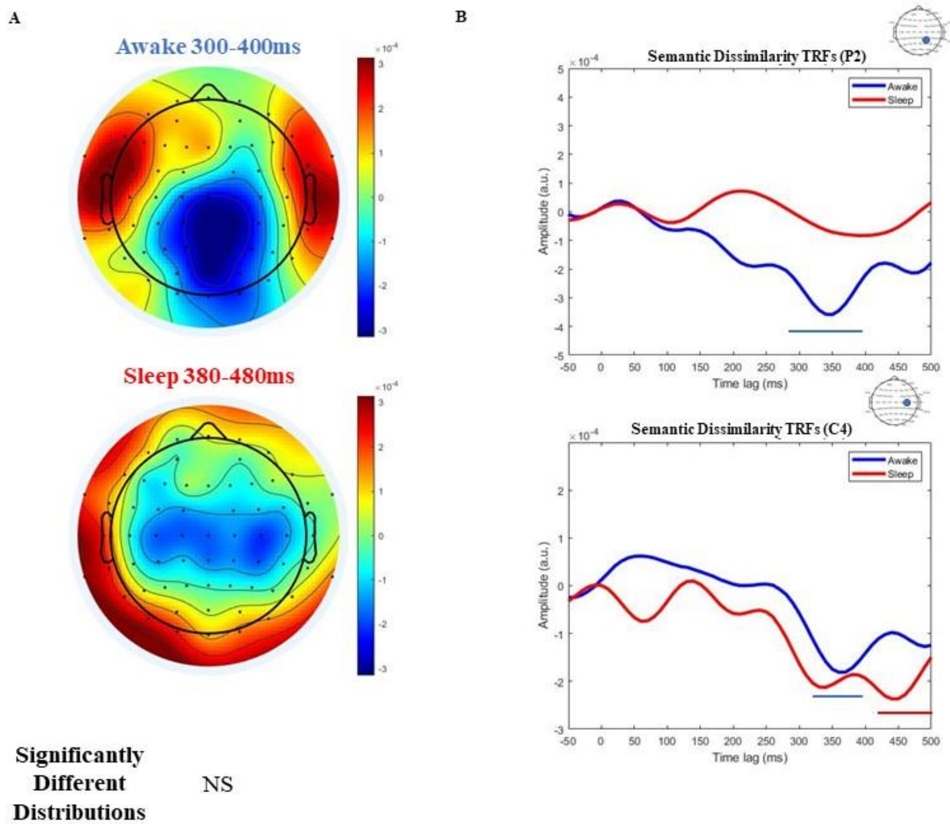

Figure 11. Semantic Dissimilarity TRFs Between Sleep and Awake Participants

A. The topographical distributions of the semantic dissimilarity TRF peak at 300-400 ms for awake participants and 380-480 ms for sleeping participants. There was no significant difference between the two topographical distributions. **B**. The TRFs developed from the linear regression of the semantic dissimilarity vector with neural EEG responses in both asleep and awake participants at the P2 and C4 electrodes. Significant TRF components for awake participants are indicated with blue bar and significant TRF components for sleeping participants are indicated with a red bar ($p < .05$, FDR corrected).

3.3.2 Intact vs. Scrambled Comparison

The next analysis compared the TRFs developed by linearly regressing the semantic dissimilarity vector of the GME audiobook to the EEG data collected from awake participants as they listened to the intact and scrambled versions of the GME audiobook. Critically, no significant peaks were observed in the scrambled version, as indicated by a running t-test against zero. In addition, the significant negative peak at 290-390 ms at the P2 electrode in the intact speech condition significantly exceeded the TRF values from the scrambled version ($p < 0.05$, FDR corrected; Figure 12B). These results demonstrate that the peaks observed to semantic dissimilarity in intact speech is specific to processing of natural, comprehensible speech and not to acoustic stimuli that have similar low-level acoustic features.

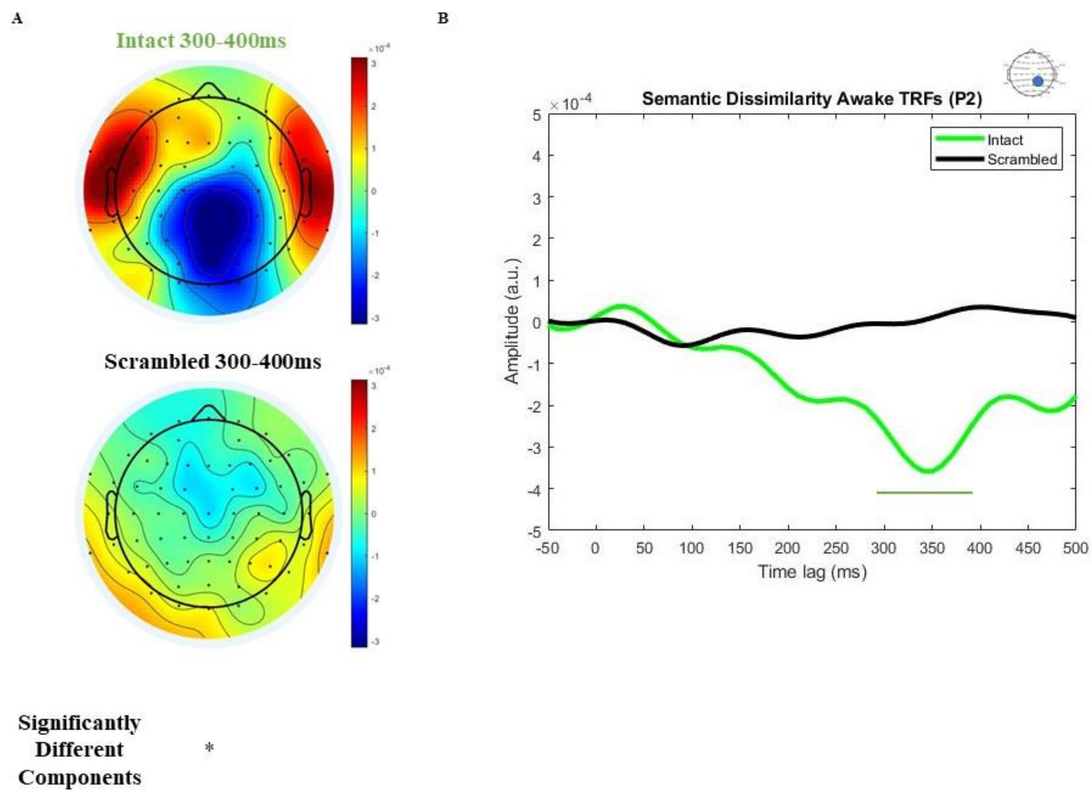

Figure 12. Awake Semantic Dissimilarity TRFs Between Intact and Scrambled Conditions

A. The topographical distributions of the intact semantic dissimilarity TRF peak at 300-400 ms and the scrambled semantic dissimilarity TRF peak at 300-400 ms for awake participants. There was a significant difference between the two topographical distributions. **B**. The TRFs developed from the linear regression of the intact and scrambled semantic dissimilarity vector with neural EEG responses in awake participants at the P2 electrode. Significant TRF components for the intact condition are indicated with a green bar ($p < .05$, FDR corrected).

Next, the TRFs developed by linearly regressing the semantic dissimilarity vector of the GME audiobook to the EEG data collected from sleeping participants as they listened to the intact and scrambled versions of the GME audiobook was compared. At the C4 electrode, in the intact condition, a negative TRF component significantly different from zero was observed at 430-500 ms (as previously reported), whereas in the scrambled condition a significant positive TRF component was observed from 350-410 ms at the C1 electrode (see Figure 13B). The topographical distributions of the TRFs were compared between the intact and scrambled conditions in sleeping participants at the time points of the significant negative TRF peak in the intact condition (380-480 ms; see Figure 13A). There was a significant main effect for the condition ($F(1,32) = 6.21$, $p = .018$), indicating that the TRF components were statistically different from one another.

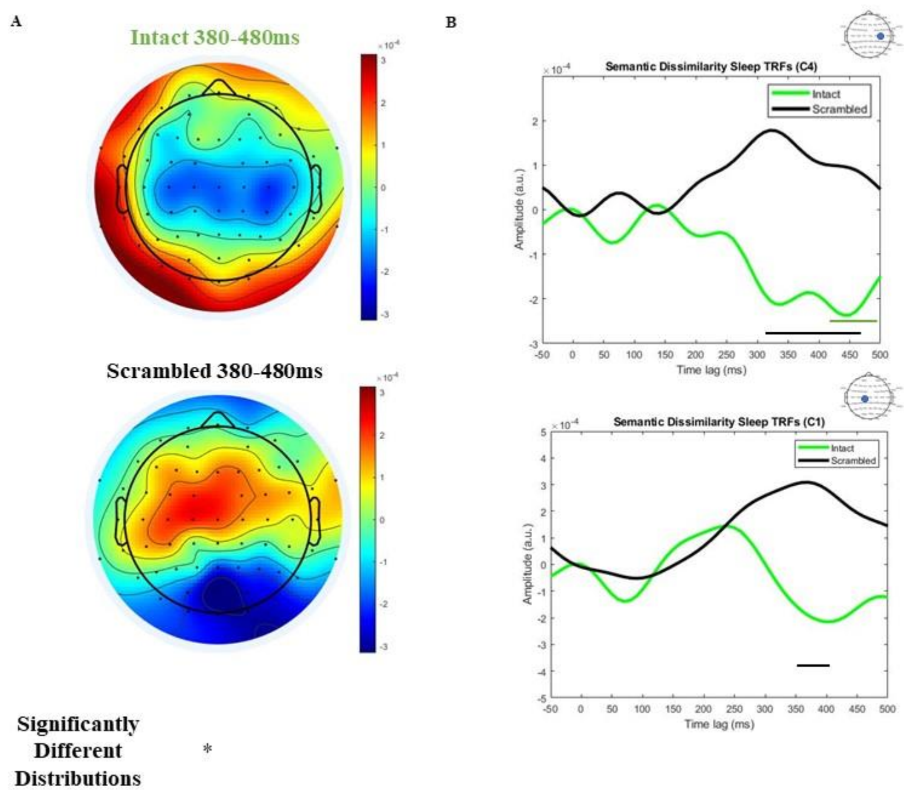

Figure 13. Sleep Semantic Dissimilarity TRFs Between Intact and Scrambled Conditions

A. The topographical distributions of the intact semantic dissimilarity TRF peak at 380-480 ms and the scrambled semantic dissimilarity TRF peak at 380-480 ms for sleeping participants. There was a significant difference between the values of the peaks. **B**. The TRFs developed from the linear regression of the intact and scrambled semantic dissimilarity vector with neural EEG responses in sleeping participants at the C1 and C4 electrodes. Significant TRF components for the intact condition are indicated with a green bar and significant TRF components for the scrambled condition are indicated with a black bar ($p < .05$, FDR corrected).

3.4 Temporal Lags of Word Onsets

Due to the unexpected result of significant deviations from zero in the scrambled sleep data for the word onset and semantic dissimilarity analyses, we hypothesized that these deviations may be a result of regular slow oscillations or delta waves synchronizing to the time lags of the word onsets. To understand if word onsets in the GME audiobook were occurring at consistently similar time lags, the frequency of the time lags for each word onset was graphed (see Figure 14). The time lags between word onsets in the GME audiobook were clustered around 150 ms (*M* = 329.54, *SD* = 498.14).

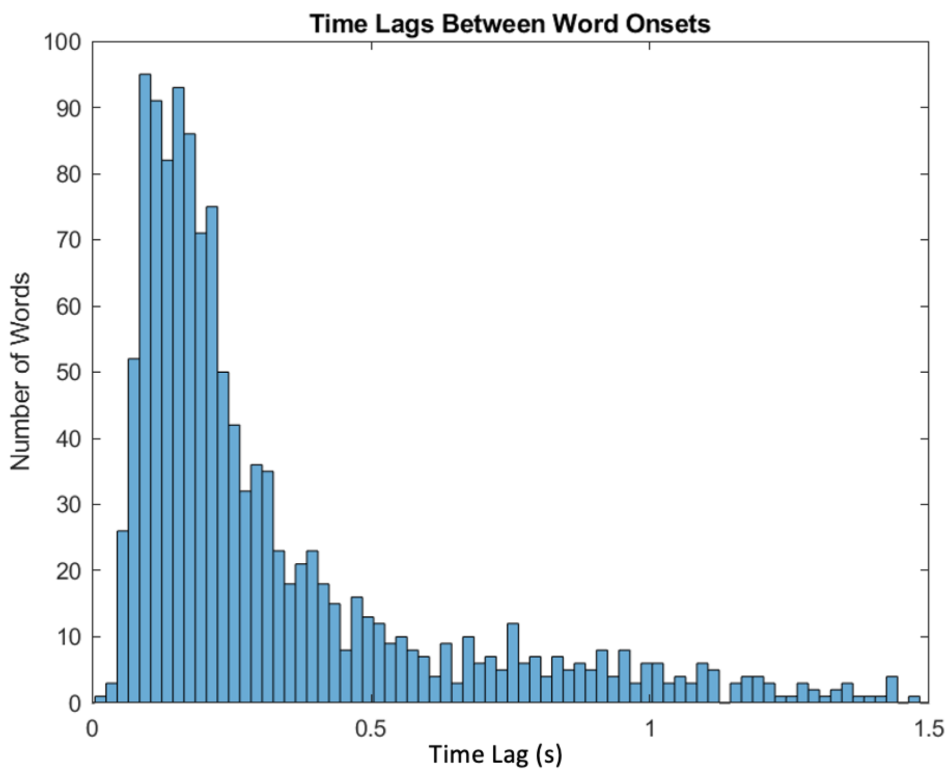

Figure 14. Frequency of time lags between word onsets in the GME audiobook

The time lags between word onsets were clustered around the 150 ms mark in the GME audiobook (*M* = 329.54, *SD* = 498.14).

Chapter 4

4 Discussion

The present study is one of the first investigations to probe the level of linguistic processing of natural, narrative speech occurring in the brain during sleep. Linear regression was used to map the temporal relationships between the (1) auditory envelope, (2) word onsets and, (3) semantic dissimilarity of the words in a spoken story to the EEG responses in both the wake and sleeping brain. In summary, the topographical distributions of TRF components related to the auditory envelope were statistically similar in both awake and sleeping participants. However, the peaks occurred at a delayed time lag in the sleeping participants as compared to the awake participants. Similarly, the topographical distributions of the TRF peaks associated with both word onsets and semantic dissimilarity were statistically similar in both awake and sleeping participants. As in the auditory envelope analysis, the peaks again occurred at a delayed time lag in the sleeping participants as compared to the awake participants. Further analyses indicated that the TRF components related to word onset and semantic dissimilarity processing were absent in the scrambled speech condition, providing evidence that these components are specific to the processing of intact, comprehensive speech. Taken together, the results suggest that the sleeping brain exhibits a remarkable preserved capacity for auditory, speech segmentation and semantic processing of natural, narrative speech during sleep, although these processes are performed at a slower rate compared to wake.

4.1 Auditory Envelope

During wake, one significant positive TRF components and two significant negative TRF component were found to reflect the mapping between the auditory envelope and the EEG response, with peak latencies are around ~50 (positive), 80 (negative), and 270 (negative) ms. A prominent non-significant positive peak was also observed at around 180 ms in awake participants. At least descriptively, similar TRF components were observed for the 50 ms, 180 ms and 270 ms components in the sleep condition at increased latencies (70 ms, 230 ms, 370 ms). However, while the TRF component at 370 ms was statistically significant, the TRF components at 70 ms and 230 ms during sleep were not significant. We nonetheless continued with the distributional comparison between sleep and wake for the non-significant peaks because qualitatively, the progression of the TRF peaks and troughs over time showed the same general pattern between sleep and wake. Although some of the components were not significant, patterns across the scalp may provide insight into whether the processes during sleep and awake were similar or not. Low statistical power and highly variable sleep data may have also played a prominent role in the non-significant results. The positivity at 50 ms in awake participants and 70 ms in sleeping participants showed a similar distribution between wake and sleep groups. In contrast, the second and third components differed between groups. For the positivity at 180 ms in awake participants and 230 ms in sleeping participants, the awake participants showed a stronger effect over anterior electrodes sites, while sleeping participants showed a maximal effect over central sites. For the negative TRF peaks found at 270 ms in awake participants and 370 ms in sleeping participants, the awake participants exhibited a strong negativity across posterior scalp regions, while sleeping participants exhibited a strong negativity in more anterior electrodes.

These findings provide some support for the hypotheses that there is a preserved level of auditory processing of natural, narrative speech occurring in the sleeping brain, as compared to wake. Although the first two TRF components in sleep were not statistically significant from zero, the 50 ms component in awake and 70 ms component in sleep shared statistically similar topographical distribution. Furthermore, over the time course, the peaks and troughs followed a qualitatively similar pattern between sleep and awake. In awake participants, the components at 50 ms, 80 ms and 180 ms were consistent with previous literature demonstrating components at 50 ms, 80 ms and 140 ms in the TRF associated with the auditory envelope of a natural, continuous speech stream (Crosse et al., 2016). These TRF components resemble the well documented P1-N1-P2 cortical auditory evoked EEG complex (Tremblay et al., 2014). The P1 potential is thought to be associated with the gating of auditory information in the thalamus and primary auditory cortex (Alho et al., 1994), the N1 potential is thought to be associated with the processing of the auditory information in primary auditory cortex (Modi & Sahin, 2017), while the P2 potential is thought to reflect higher level auditory processing in association cortex (Modi & Sahin, 2017), as its amplitude tends to increase with age and learning (Crowley & Colrain, 2004). The brain's inability to effectively use the higher order capabilities of the prefrontal cortex during sleep may reflect the difference in topographical distribution of the second positive ("P2-like") TRF component, occurring at 180 ms in awake and 230 ms in sleep (Figure 4B).

The final negative peaks at 270 ms in awake participants and 370 ms in sleeping participants may be related to the N200 ERP commonly observed at around 180 to 325 ms following the presentation of an auditory stimulus (Patel & Azzam, 2005). This negativity is often elicited in response to deviations in the form or context of an auditory stimulus, and it is commonly associated with attention and stimulus discrimination (Patel & Azzam, 2005). The peaks at 270 ms and 370 ms are localized over parietal regions of the scalp, sharing similar topographical distributions as the N200 ERP. Thus, the negative TRF peaks observed in the current study may reflect the perceptual discrimination of the varying intonations and tones of voices used in the audio excerpt of GME.

It was intriguing to note that the TRF peaks in the sleeping brain occurred at delayed time lags as compared to wake, indicating that low-level auditory processing may be occurring at a slower rate in sleeping participants. The increased latency of TRF components during sleep relative to wake is consistent with previous research that identified delayed latencies of the P1 ERP, along with a later auditory evoked negative potential at N340 in response to frequent tones during NREM2 sleep (Nielsen-Bohman et al., 1991). The N200 ERP component has been documented to occur at increased latencies during sleep (Wesenten & Badia, 1988). The delayed onsets of these EEG markers of auditory processing may reflect the slowing down of neural oscillatory activity during NREM2 sleep (Adamantidis et al., 2019).

In awake participants, the sequence of TRF components observed to intact speech was eliminated when participants processed scrambled speech. However, during sleep, the TRF components remained relatively intact to scrambled speech, albeit at a delayed latency. During wake in the scrambled speech condition, there was only a single significant positive TRF peak occurring at 60 ms (Figure 5). Sleeping participants also showed a positive TRF component at 230 ms with a similar topographic distribution, though this component was not significantly greater than zero. However, the sleeping brain also exhibited prominent components at about 300 ms and 360 ms, resembling a delayed P1-N1-P2 auditory complex (Figure 7). The absence of an auditory TRF auditory complex in wake may be a result of the awake individual's ability to use top-down processing to quickly discern that the scrambled speech sounds are irrelevant to them. As a result, they can filter out the auditory information at a relatively early processing stage, and not process it any further. In contrast, during sleep, the brain is continuously monitoring its external environment for salient events (Blume et al., 2018). Lacking the ability to filter out obviously irrelevant or nonsensical information, the sleeping brain may instead continuously process the scrambled speech stream to ensure that the sounds do not pose any harm to the individual. All in all, these results showcase that there is a preserved but slower level of auditory processing of natural, narrative speech occurring in the sleeping brain.

4.2 Speech Segmentation

In awake participants, a significant positive TRF peak at 100 ms and a significant negative TRF peak at 350 ms were associated with word onsets. Similarly, sleeping participants showed a similar, albeit somewhat delayed, sequence of peaks, consisting of a broad significant positive peak at 210-260 ms and a significant negative TRF peak at 400 ms (Figure 8). The 100 ms positive TRF peak has been identified in previous literature to be associated with speech segmentation processing in awake individuals (Brodbeck et al., 2018). This study also reported that this effect showed numerically larger values over the left hemisphere, though this lateralization was not significant. In the current study, the positive peak at 100 ms in wake and the 210-260 ms positive peak in sleeping participants shared a statistically similar topographical distribution, with a maximum over left lateral areas of the brain (Figure 8). The left hemisphere lateralization in the 100 ms and 210-260 ms positive peaks may reflect the well-known dominance of the left hemisphere in language processing for most humans (Ries, Dronkers &, Knight, 2016).

Contrary to our original hypotheses, where it was predicted that the sleeping brain may exhibit a diminished level of speech segmentation processing of natural, narrative speech, these findings demonstrate that speech segmentation processing of natural, narrative speech is preserved in the sleeping brain. These results contradict the findings from Makov and colleagues' (2017) investigation that suggests that only low-level auditory processing is preserved during sleep. However, this inconsistency could be a result of the speech stimuli that Makov and colleagues used. Their stimuli consisted of well-controlled yet artificial sequences that followed strict linguistical patterns, with each syllable presented at an isochronous rate. Furthermore, they removed all prosodic and acoustic cues to word, phrasal and sentence boundaries from the audio recording. In addition, each sentence was contextually isolated, rather than contributing to a broader narrative context or story, as in the present study. Due to this unnaturalness, the speech stimuli may not have been engaging or emotionally relevant enough for the sleeping brain to process effectively. Similar to the auditory processing findings, the latency of the positive peak was far greater in the TRF associated with sleeping participants than the TRF associated with awake participants, signifying that speech segmentation processing of natural, narrative speech occurs at a delayed rate during sleep. Again, this may be driven by the slower oscillations occurring during NREM sleep or slower bottom-up processing of acoustic information.

In addition to the early positive peak, a later negative peak was discovered in both groups, occurring at 350 ms in awake participants and 400 ms in sleeping participants (Figure 7). The negative TRF peaks in both sleep and awake participants shared similar properties to the well-defined N400 ERP response, exhibiting a strong broad negativity across 200-600 ms. The negative peaks also showed statistically similar topographical distributions between sleep and awake participants, with a maximal effect over posterior midline electrode regions. This result provides initial evidence that there is a preserved level of semantic processing of natural, narrative speech occurring during sleep. This will be discussed further in the semantic dissimilarity analysis section.

As expected, for wake participants listening to scrambled speech, the TRF associated with word onsets exhibited no significant peaks across the entire time course (Figure 9). However, somewhat unexpectedly, sleeping participants listening to scrambled speech showed a significant positive TRF peak from 300-450 ms (Figure 10). To the extent that there is a significant oscillatory component at 3-4 Hz during NREM sleep, a phase-locked component may emerge as the result of the pseudo-regular epoching of the signal to word onsets, as most time lags occurred at around 150-250 ms time lag intervals (Figure 14). In addition, it is also important to note that the scrambled speech stream did not consist of completely random noise but retained some of the spectrotemporal features of the original audio script over longer timescales (e.g., intonation patterns, prosody). Thus, it is possible that there were subtle rhythmic acoustic features even in the scrambled version of script, and that some neural entrainment or neural synchrony of the ongoing slow oscillations may have occurred to the semi-predictive word onsets during sleep. This may not have occurred during wake, as the audio signal may have been filtered out at a relatively early stage in processing. Nonetheless, the TRF components present in the intact speech version are notably absent in the scrambled speech version (Figure 9), demonstrating that semantic and speech segmentation processing is occurring preferentially when participants listen to the intact script compared to the scrambled script. All in all, there is evidence to support that there is a preserved level of both speech segmentation and semantic processing of natural, narrative speech occurring in the sleeping brain.

4.3 Semantic Dissimilarity

Similar to the speech segmentation TRFs, wake participants showed a significant negative peak at 350 ms in the TRFs associated with semantic dissimilarity. Similarly, in sleeping participants, there was a significant negative TRF peak observed at 450 ms (Figure 11). These negative TRF components shared similar characteristics to the N400 ERP component, which typically appears as a strong, broad negativity from 200-600 ms (Kutas & Federmeier, 2011; Ledwidge, 2018). This result is also consistent with a previous TRF investigation that identified a strong negative TRF component at around 400 ms when awake participants listened to natural, continuous speech (Broderick et al., 2018). However, in contrast to our original hypotheses which predicted a diminished level of semantic processing occurring in the brain during sleep, the topographical distributions of the negative peaks in awake and sleep participants were statistically similar. This coincides with previous literature that have shown that the sleeping brain is able to perform semantic processing of single words and word pairs during sleep. For example, Ibanez et al. (2014) were able to show that highly incongruent words elicited an N400-like component during both awake and sleep. Furthermore, Portas et al. (2000) were able to exemplify that the same regions of the brain are activated when an individual's name is presented while they are awake or sleep. Our results build upon and extend these findings, indicating that semantic processing of *fully natural*, narrative speech is preserved in the sleeping brain.

As expected, in wake participants, the semantic dissimilarity analysis applied to scrambled speech revealed no significant TRF peaks (Figure 12). Furthermore, the topographical distributions of TRF activity associated with the intact and scrambled conditions in awake participants at 300-400 ms were statistically different, providing further evidence that this strong negative TRF component is associated with the semantic processing of words in a natural, narrative speech stream. However, the TRF developed from sleeping participants listening to scrambled speech exhibited a significant *positive* TRF peak at 310-460 ms, similar to the effect observed to scrambled speech in the word onset analysis. Again, a possible explanation for this occurrence may be that the slow oscillatory activity in the brain during NREM2 sleep synchronized to semi-predictive acoustic regularities that were maintained in the scrambled speech condition. However, another possible explanation may be that the positivity is indexing a delayed P300 response in sleeping individuals. The P300 ERP component is related to an individual's ability to detect and respond to certain stimuli (Wesenton & Badia, 1988). Its amplitude is related to attentional engagement and is diminished under conditions of passive listening (Wesenton & Badia, 1988). Unexpected and dissimilar semantic words may be potentially correlated with certain acoustic features, such as a louder tone of voice, greater emphasis or pauses in speech. These acoustic features may have been maintained in the scrambled version of the GME recordings and may reflect the positivity observed in the semantic dissimilarity TRF for scrambled data. This positivity response may not have been found in awake individuals, because they would have the executive capacity to understand that the scrambled sounds were irrelevant and could be subsequently tuned out. However, the sleeping brain is tasked with continuously monitoring its environment for salient information (Formby, 1967) and thus, more of the auditory signal may be processed in the scrambled speech condition, albeit in a delayed manner. This explanation remains speculative and future research will look at applying the same semantic dissimilarity vector to natural sleep EEG data without any auditory stimulation, in order to test whether the scrambled speech stimuli, as opposed to the general analysis procedure as applied to the sleep data, are responsible for this effect.

All in all, this investigation is one of the first to provide evidence of a preserved level of semantic processing of natural, narrative speech occurring in the brain during sleep.

4.4 Limitations and Future Directions

Although there were significant differences observed throughout a variety of topographical distributions and TRF peaks in these analyses, there is still the potential of low power playing a role in the lack of significant differences found in the sleep auditory envelope TRF peaks. Low power may have played a more significant role in the auditory envelope analysis than the semantic dissimilarity and word onset analysis because the auditory envelope analysis involved mapping a relationship with the data at each time point, whereas the semantic dissimilarity and word onset analysis involved mapping relationships at the time of each word onset. As a result, the auditory envelope analysis may have been more susceptible to variability in the data, as the model aimed to incorporate a relationship for a variety of time-aligned acoustic features within the auditory envelope. More participants should be tested to ensure the validity of the trends discovered during these analyses. Due to the predictive nature of the time lags between word onsets, it was difficult to interpret the significant TRF peaks observed in sleeping participants as they listened to the scrambled version of the GME script.

Another limitation of this study was that the stage of sleep in which the GME script was presented to participants could not be controlled for. Although the GME script was started once the participants entered stable NREM2 sleep, participants were still able to shift between stages of sleep as the script was played. As a result, some participants may not have processed the GME script if they entered NREM3 sleep. Future investigations could test linguistic processing of natural, narrative speech during nocturnal sleep, in which stages of sleep are longer and more stable. Nocturnal speech may also be better suited to investigating how different sleep stages influence linguistic processing of a continuous speech stream. Additional future directions for this line of research could look at directly comparing the topographical distributions and wave functions of notable ERP components with the TRF components developed from the linear regression method. This will provide us with a further understanding about the significance of the TRF components discovered in this investigation and connect it to the older and much more extensive ERP literature.

Finally, a key limitation in this investigation lies in the constraints of the EEG methodology. Although, two TRFs may display statistically similar topographical distributions, we are unable to unequivocally conclude that the exact same neural processes are occurring in the brain for the two conditions. EEG allows for the observation of electrical activity at the scalp; however, the neural sources of this electrical activity cannot be definitively established. Future work with additional neuroimaging techniques such as functional near-infrared spectroscopy (fNIRS) and fMRI may provide further clarification on the relationship of neural activity during sleep and wake.

4.5 Conclusion

This investigation was one of the first of its kind to understand which features or types of information can be extracted from natural continuous speech during sleep. Understanding the linguistic processing capabilities of the sleeping brain has implications for our understanding of the levels of conscious awareness during sleep. Furthermore, this investigation provides insight into the overall cognitive capabilities of the sleeping brain. The evidence from this investigation demonstrates that there is a preserved level of low-level auditory processing, speech segmentation processing and semantic processing of natural, narrative speech occurring in the brain during sleep. Furthermore, it showed that linguistic processing of natural, narrative speech occurs at a slower rate during sleep, across all three types of analyses. The processing of auditory information during sleep likely serves an important adaptative purpose, allowing an individual to detect relevant or emotionally salient stimuli outside of consciousness awareness and to continuously monitor for stimuli that may harm them as they sleep. This further supports the consensus that sleep is represented as an altered state of consciousness, rather than a state of unconsciousness (Rasch & Born, 2013). New research has continued to come out to showcase the amazingly advanced capabilities of the sleeping brain. For example, a recent study demonstrated that the sleeping brain is able to solve math problems and communicate answers to an experimenter in real-time, using interactive dreaming (Konkoly et al., 2021). The findings from this investigation unearth yet one more example of the sleeping brain's advanced cognitive abilities.

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Appendices

Appendix A: Ethics Approval

Date: 24 August 2020

To: Dr Laura Batterink

Project ID: 112576

Study Title: Studies of sleep and language learning

Application Type: Continuing Ethics Review (CER) Form

Review Type: Delegated

Meeting Date: September 4 2020

Date Approval Issued: 24/Aug/2020

REB Approval Expiry Date: 31/Aug/2021

Dear Dr Laura Batterink,

The Western University Non-Medical Research Ethics Board has reviewed this application. This study, including all currently approved documents, has been re-approved until the expiry date noted above.

REB members involved in the research project do not participate in the review, discussion or decision.

The Western University NMREB operates in compliance with the Tri-Council Policy Statement Ethical Conduct for Research Involving Humans (TCPS2), the Ontario Personal Health Information Protection Act (PHIPA, 2004), and the applicable laws and regulations of Ontario. Members of the NMREB who are named as Investigators in research studies do not participate in discussions related to, nor vote on such studies when they are presented to the REB. The NMREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000941.

Please do not hesitate to contact us if you have any questions.

Sincerely,

The Office of Human Research Ethics

Note: This correspondence includes an electronic signature (validation and approval via an online system that is compliant with all regulations).

Appendix B: Consent Form

Project Title: Studies of Sleep and Language Learning

Principal Investigator:
Dr. Laura Batterink

1. Invitation to Participate
You are being invited to participate in a research study about how the role of sleep in memory consolidation and language learning.

The purpose of this letter is to provide you with information required for you to make an informed decision regarding participation in this research. It is important for you to understand why the study is being conducted and what it will involve. Please take the time to read this carefully, and feel free to ask questions if anything is unclear or if there are words or phrases you do not understand.

2. Why is this study being done?

The purpose of the study is to investigate how sleep contributes to the learning, consolidation and retention of different aspects of language, such as vocabulary and grammar. The results from this research will help us understand how sleep contributes to language learning, including clarifying whether sleep plays a more central role in learning some aspects of language compared to others. Our results will also help to pinpoint the underlying physiological mechanisms during sleep that may contribute to language learning and consolidation. This research has important implications for adult second language learners and may eventually lead to novel methods of boosting second language learning and retention through sleep.

3. How long will you be in this study?

It is expected that this study will take approximately [# of hours 3 - 5] hours to complete.

4. What are the study procedures?

The experiments conducted as part of this study will test how humans process and learn about different types of linguistic stimuli, such as syllables, words, phrases and sentences. If you agree to participate, you will be asked to listen to language-related auditory stimuli and/or read words and sentences on a screen. You may be asked to perform different tasks associated with the stimuli, such as responding to targets by pressing a button, or making different judgments or ratings about your impressions of the stimuli. You may be asked to respond using your voice, and your voice may be recorded using an audio recorder. If you do not wish to be recorded, you can still participate in other parts of the study.

Your brain activity will be recorded using a technique called electroencephalography (EEG), where electrodes placed on the scalp measure electrical signals that brain cells use to communicate. An elastic cap will be placed on your head. The cap will be strapped down to fit snugly and comfortably. The sensors, which look like white pieces of plastic about 1 inch in diameter attached to the cap, will be filled with a small amount of conductive gel. To monitor blinking and eye movements, the experimenter will place similar sensors on the skin surface near your eyes. These sensors will be secured in place using tape. When the sensors are removed, the gel will be wiped off using tissue. Some gel may remain in your hair, but it can easily be removed by rinsing with water. You will be given the opportunity to wash your hair at the end of the study.

You will be given the opportunity to take a nap in the sleep lab in the Western Interdisciplinary Research Building (WIRB) while your brain activity is recorded using EEG. Each room in the sleep lab is equipped with a comfortable bed. You will be asked to lie down in the bed for a [1-2] hour period. While you nap you will be monitored using video and audio monitoring equipment by the experimenter in an adjacent room. The experimenter will be available throughout the nap if needed, and you can communicate with the experimenter at any time during this nap opportunity through use of the 2-way audio monitor.

The task(s) will be conducted in the Brain and Mind Institute in the Western Interdisciplinary Research Building (WIRB) on the University of Western Ontario campus.

5. What are the risks and harms of participating in this study?

There are no known or anticipated risks or discomforts associated with participating in this study. However, you may experience a minor inconvenience as some gel may remain in your hair at the end of the study. The gel can easily be removed by washing your hair. You will be given the opportunity to wash your hair at the end of the study.

6. What are the benefits?

You do not directly stand to benefit from this study. Although you may not directly benefit from your participation, the information gathered may provide benefits to society as a whole which include enhancing our scientific understanding of sleep, memory consolidation, language, learning, and the brain, and leading to advancements in second language training and treatment of language-related disorders (for example, specific language impairment and autism).

7. Can participants choose to leave the study?

You may refuse to participate, refuse to answer any questions or withdraw from the study at any time. If you decide to withdraw from the study, you have the right to request withdrawal of information collected about you. If you wish to have your information removed please let the researcher know. Withdrawing or refusing to answer questions will not result in loss of promised compensation.

8. How will participants' information be kept confidential?

Any personal or identifying information obtained from this study will be kept confidential and will be accessible only to the investigators of this study. Identifiable information that will be collected during the study includes your full name, telephone number, email address, partial date of birth (month and year) and, in some cases, audio voice recordings. In the event of publication, any data resulting from your participation will be identified only by case number, without any reference to your name or personal information. Only the research team will have access to information that identifies you to carry out this research study.

If files are shared with other researchers or the results are made public, any personal information that could identify you will be removed. Only anonymized data will be shared outside the research team (e.g., in an open access repository for publication purposes, or for other researchers to verify the findings or re-analyze).

Any documents identifying you by name will be kept separately from your data, and will be destroyed after 7 years. De-identified and anonymous study records will be maintained for a minimum of 7 years. A list linking your study number with your name will be kept by the researcher in a secure place, separate from your study file.

Representatives of the University of Western Ontario Non-Medical Research Ethics Board may require access to your study-related records to monitor the conduct of the research.

9. Are participants compensated to be in this study?

You will receive course credit (1 credit per hour) or monetary compensation ($14 per hour) for your participation in this study. If you do not complete the entire study you will still be compensated a pro-rated amount (based on the same rates specified above: 1 credit/h or $14/h). When calculating prorated compensation, your total participation time will be rounded up to the nearest half hour. For example, if you withdraw after 1 hour and 15 minutes, your participation time will be rounded to 1.5 h and you will receive 1.5 credits or $21. Therefore, even if you withdraw prior to completing study, you will still be compensated for the amount of time you spent participating.

10. What are the rights of participants?

Your participation in this study is voluntary. You may decide not to be in this study. Even if you consent to participate you have the right to not answer individual questions or to withdraw from the study at any time. If you are a student at Western and you choose not to participate or to leave the study at any time, it will have no effect on your academic standing.

We will give you new information that is learned during the study that might affect your decision to stay in the study.

You do not waive any legal right by signing this consent form

11. Whom do participants contact for questions?

If you have questions about this research study please contact Laura Batterink, Principal Investigator,

If you have any questions about your rights as a research participant or the conduct of this study, you may contact The Office of Human Research Ethics

This letter is yours to keep for future reference.

Consent Form
Project Title: Behavioral and EEG studies of language learning
Study Investigator's Name: Dr. Laura Batterink

I agree to be audio-recorded in this research.

☐ **YES** ☐ **NO**

I agree to be contacted for future research studies.

☐ **YES** ☐ **NO**

I have read the Letter of Information, have had the nature of the study explained to me and I agree to participate. All questions have been answered to my satisfaction.

Participant's Name (please print): ____

Participant's Signature: ____

Date: ____

My signature means that I have explained the study to the participant named above. I have answered all questions.

Person Obtaining Informed Consent (please print): ____________________________

Signature: ____________________________

Date: ____________________________

Appendix C: Script for John Butler Interview

John: John: [Nods head], mmm, he was a quiet man, an artist, a craftsman. Very conscious of his surroundings. A landscape artist mostly at that time. So, he taught me to observe nature, to see the beauty of what was in front of me. Nothing elaborate, just the hedges, the trees, the grass, to notice the sky. He was also very conscious of good work. He loved carpentry, he taught me how to use tools and I remember so well him saying "pay attention, keep your eye on what you are doing. When you are sewing a piece of wood, listen to and watch the movement of the saw, watch the hammer so that you hit the nail straight. And these two lessons of 100% giving attention and observing what was around me have stood me in good stead all my life.

Iain: They're wonderful qualities which are probably quite rare these days which is sad but that is the way the world is…and what did you get from your mother?

John: Mum was Russian. Well, she was also an artist in her way. She was a housewife of course, which is what women were then they called themselves that and were proud of it. Mum was always, when Women's Lib[eration] came in she said there is nothing wrong with being a mother and a housewife. Anyway, what I got from mum was primarily a Russian heart and Russian hearts they just spill out all over the place. And I was always told as a child that I wear my heart on my sleeve, well, people laughed at me but it is one of the best things, to have a great heart. To work from the heart, to recognise the existence of the heart and the whole household shone with that tender loving care that emanates from someone that loves their work and gives themselves to it; the way the table was laid, the way she knitted our clothes for us, did the mending, did the washing up, everything was a work of art and done with love.

Iain: And I know at seven years of age you were sent to boarding school and that was a little bit of a shock but you escaped to the chapel and pray when you needed didn't you, to find your solitude and balance again.

John: [Laughs] It was a shock because up till then we had lived in the deep country and I hardly knew what another little boy was. My companions were nature and animals. And I was suddenly thrown into this world of other little boys and I was completely lost and for the first time in my life I knew what it was to feel isolated and lonely. And God the school was in a rural setting so there were big gardens where I could go and, also in my little childish way I remember so well just burying my little head in my hands and closing my eyes and saying God bless mummy and daddy and my sister and our dog and what a haven of home and security that was for me.

Iain: It seems even at an early age you had a way of going inside and finding somewhere you could rest, as you used the word *haven* just now.

John: Yes, I think that probably was so, if not inside, at least to stillness and quietness. In nature, it is outside, isn't it? You look at a tree and put your arms around a tree and you're held in stillness, in quietness, in that reassurance of simply being itself. And what a contrast it is to the noise and the agitation that you get from most people.

Iain: And you talk about, I don't know if you remember, at the beginning of this book [*Wonders of Spiritual Unfoldment*] you talk about, it's a book about [being] committed to discovering stillness.

John: Well I wouldn't say that, no, it is really a book committed to discovering…well, I don't really know what really…if I use clever words like the Infinite, or even God it, as a young man I wasn't, I still don't know really what they are, who does know what God is [laughs]? Nobody knows what God is, but there's, how can I put it? Perhaps one longs for the unlimited, for freedom and for love and any worldly experience, all these things are finite; they have an end. You go out, you discover freedom, go out and climb a mountain but then you have to come home again. Love is wonderful in its flowering but then sooner or later it says "no", it has an end. All the things you love, the happiness, it all comes and goes, doesn't it? I think that perhaps I was just greedy, I wanted that which didn't end.

Iain: but sometimes we need that, you call it *greed*, that commitment to find, otherwise we never find it.

John: Well, absolutely, that's the motivation, isn't it?

Iain: We will come on to that a bit litter, I just want to go through your story a little bit sequentially and just discover these important pointers in your life. So, there's so much we could do because you are now seventy-nine years old, there's so much we could talk about but I'm going to summarise it to some extent: You were an army officer, which I guess was National Service, involved with the family business and then in 1963 you went to South America…

John: Yes.

Iain: What's the reason you went to South America?

John: Oh, I wanted to make the world a better place [laughs]. **Iain:** What was your vision of making the world a better place?

John: Well, I was a farmer, I'd loved farming since my first breath, I was soaked in farming. I wanted to be a farmer, it was my overriding dream really. And I had spent some time, I had studied the subject and it was the time when these charities like OXFAM were just beginning, so it was the fashionable thing really, I suppose. I had another mate and we were going out to Bolivia, we were going to take a…they were giving grants of a thousand hectares to new settlers who would go out and grow food for the hungry, so we thought we would go out and do that. We were young and strong but my mate didn't come, he met a girl who stayed in England and I met a Peruvian girl and her father invited me to go and work for him in Peru, so I did that on a big sheep hacienda. But that was my Socialist time of life and I wanted to do good so I ended up working as a volunteer agriculturalist in the mountains of Peru.

Iain: Which must have been beautiful, actually.

John: Uh huh [nods head].

John: Well I wouldn't say it was easy but there was plenty of space up there and I loved that, I loved the donkeys and the oxen. And yes it was a good year but I think like most people who had done voluntary service, I learnt, it gave me much more than I gave to it really and I learnt probably the greatest lesson of my life: I remember sitting on a mountainside one day, I had done a lot of work and a little bit of work planting trees on eroded mountainsides and of course the local sheep and goats had come and eaten them all off, so I was sitting there a bit depressed. And it seemed, a little voice said to me "make whole, be whole."

Iain: Make whole, be whole.

John: To make whole, be whole. Well I hardly understood what that was then but I had read a little bit about meditation, not that I really understood it. But I saw myself as a mixed-up young man trying to help people, the local Indians, who were older and wiser than myself and more able to live. And I realised I had to do something about sorting out myself before I could be much use to others. So, having read a bit about meditation, when I came home to England, I looked for and I found a school of meditation.

Iain: I wanted to just point out one more thing that I thought was important in your book was, there was a situation, you were in the mountains, in the jungle I think in Peru and you felt the only way was to *surrender*.

John: Ah, yes [laughs].

Iain: Do you remember that? That was quite important I think.

John: Yes, I had a pal and we'd found an Indian who would take us, and we had several days in the jungle, just walking through the jungle which was…

Iain: …it must have been an incredible experience.

John: It was an incredible experience, it was absolutely wonderful. The jungle is very thick it is quite difficult to walk through, with great trees above us, very little sunlight comes down to the forest floor, you creep along over the fallen leaves, these huge lizards, snails and snakes, you see monkeys up in the trees and at one point we came to a little creek with sandy banks and there was a great sought of furrow gouged out of the sand as though someone had dragged a big oil barrow through it. And we looked at the guide and it was a huge snake, an anaconda and I wanted to follow up and find it but he wouldn't let me, he said it would be lying curled up ready to grab us. And then it started to rain and we camped just near there, just beside it and we made a little fire, just sleeping on the ground there and I didn't sleep very well, I think maybe I woke up in the middle of the night and the rain had cleared, and you know the jungle's full of shrieks and funny sounds, rustlings at night, all the animals come out and move around and I sat there by the campfire, in this little circle of light and I thought of this great snake, I could reach out and touch it probably for all I knew. And I began to feel fear and we were alone in this jungle and if the Indian deserted us God knows what we would have done. And then quite inexplicably I just, perhaps I had stopped fighting, I gave up the struggle, I surrendered. I just relaxed into the situation as it was, into the unknown and I suddenly felt peace, such as that I'd never felt before. Just total peace, in which all the threats that surrounded us were contained and alright. And I look back on that as one of my first great spiritual experiences.

Iain: Yes, you say in the book "I put my trust in forces greater than me."

John: Yes.

Iain: Yes, which we all have to do, don't we sometimes, if not all the time?

John: Yes, in a way, I've been doing it all my life. That is the essence.

Iain: [Reading from the book] "putting your trust in forces greater than you."

John: That's right.

Iain: Yes. Do you feel that peace now?

John: Absolutely.

Iain: Yes

John: Of course. I am nervous before an interview but what do I do? I find that stillness and I feel confident, it's like an invisible hand to hold, a rock.

Iain: So how do you find the stillness?

John: How do I find it? Well it can't be described.

Iain: Yes and you said you were nervous before the interview and you find that stillness…

John: …yes, how do I find it? I've had many years of practice, it is second nature to me now. Probably my first nature. It is so obvious, we are sitting in it like fishes in the sea. You can never not be still but the trouble is we just don't see it. We look down and we just live in this cocoon of mental agitation [covers his eyes with his hands], lost in thought; that's the human condition. At least what we call the human condition, but actually it's lost, it is not reality at all, what we are, and that is the cause of all of our problems. We are absent from the presence of God.

Iain: And this in a way, the groundwork is what your father was teaching you, about watching the now…

John: yes, to be present, to be present. The present is such an important word, now, the present moment here and now. The present moment…[the church bells begin to chime]…you can hear the church clock chiming, can't you?

Iain: I can.

John: It is sounding in stillness, isn't it?

Iain: It's one o'clock…

John: …in stillness and in timelessness. Time goes round, round and round in eternal presence, the peace of God that passeth understanding, right here and now, you can never be closer to God than right here and now.

Iain: Okay, so I am going to keep going with your story, see what else comes out of that. You were starting to say that when you got back from South America you were twenty-seven and you discovered this school of mediation.

John: Yes.

Iain: Tell us about that, about how you discovered it, not so much how you discovered it but how it was important to you.

John: Well, it certainly was very important. Yes, I had to go to London to be taught, I was taught. My first farm was at Bakewell then, so I had to get the late night train back from London to look after my animals the next morning and I was sitting in St Pancreas station waiting room, among all the rubbish and the unfortunate drunks and homeless that used it and I sat and closed my eyes and meditated as I had been told and there and then in that seemingly uncongenial situation it opened up, like that [raises his arms high] and I realised that all the space, the freedom that I had longed for and that I had been travelling the world to find, the deserts and the mountains of this world where within me, and that discovery, that discovery, well it has been going on ever since. Bigger and bigger, greater and greater, better and better.

Iain: So the discovery was the beginning of something in a way.

John: It was the beginning of realisation. Of course, I had the theory, I was brought up in a Christian school, I had ten years of compulsory chapel and scripture lessons, I knew a lot of the Bible by heart and the old prayer book; “The kingdom of God is within you,” you know I’d learnt that but what did it mean? I didn’t really know but very soon in those first few periods of meditation I had realised there was this dimension that was not of this…not what we call…this world. There was a further dimension that could be realised. That’s the word *realisation*. The Biblical phrase comes alive *The Kingdom of God*, what does that mean, I don’t know it’s difficult to say even now but it’s within you, it really is within. And the peace of God that passes understanding, it is beyond the thinking mind. You don’t get it by substituting one thought for another but by opening-up to this dimension of spirit really, that's what it is. Invisible. You can't describe it. Everybody knows what silence is but no one can describe it. Who knows what silence is?

Iain: I'm not sure that everyone knows what silence is actually. They think it's just not hearing any noise.

John: Well, exactly.

Iain: We will go into more detail later but I think there is almost an art to silence somehow. I know you had some, again, important experiences which helped deepen your realisation, there was one time when you were on the underground train in London and you saw everyone as Jesus, is that right?

John: Well I know I used the word when I described it, but I'm not sure really what I meant by it. I think the words *Jesus* and *Christ* so often get used with very nebulous meaning and different people of course mean it in different ways but I think how I would describe it now as far as I remember, it was this realisation of this stillness, that there in this underground carriage was full of this stillness and within this stillness the bodies, the sounds, the personalities took place and actually pervaded everybody.

Iain: Whether they realised it or not.

John: Oh absolutely, I mean if you look at people's eyes, everybody every eye shines with more or less light even if the eye is very dull, it is the same light isn't it, how many lights are there? There is only one light isn't there? And so, it is, there is only one stillness, there's only one stillness. And I think these first experiences of mine were like that.

Iain: You had another time when I think you were also in London where even you saw the garbage as beautiful, everything was shining.

John: Yes, well again it depends what you're focussed on. There are levels of consciousness, if your heart is light, if your heart is full of light, you see light. And everything that is in it is light, you know beauty is in the eye of the beholder isn't it, if your eye is full of beauty that's what you see.

Iain: Yes but I think it was also important from what you explained in the book about that realisation, I am just trying to find the words here [from the book] that forced you to review some deeply negative attitudes towards civilisation's city life.

John: Absolutely, yes, well I think I said, being a country boy I was at that time very negative about city life as a sort of worst of the worst [laughs], you know we used words like *Townies* to describe those not fortunate enough to live in the country and civilisation was the very antithesis of nature. Unnatural wasn't it, and so these were some of the great lessons I had to overcome and certainly meditation did help to clear-out some of those negative thoughts from my mind but unfortunately there were many, many more of them deeply buried inside, it is a long process.

Iain: It is a long process and I think that one of the things that comes across, certainly in your book and your story is this motivation, this determination to keep going somehow, you didn't give up. Let's go through the story and we'll come to some examples of this, so in your thirties you were, you actually thought of becoming a monk at one point, you were in and out of monasteries, you were searching still in the Christian tradition I guess there.

John: Mmm, yes, I don't remember too clearly what my motivation was, I think perhaps it was a reaction you know I didn't want to be what most of my contemporaries were, I didn't want to go into business, I didn't want to go into the professions. Monastic life seemed to offer an alternative but that was about the same time as I learned to meditate and it certainly raised the question do I follow this way or the way of meditation? I don't see any conflict now but then I did it seemed an either/or situation. At that time…things have changed a lot in that last fifty or sixty years, the Church was really, quite suspicious of meditation it, it regarded it as something Eastern which is very odd, but anyway it did and I guess I was caught up in that but anyway I decided to stay with meditation, because even in those early months I realised, or I felt it was, at least for me a more effective way of spiritual work.

Iain: You say more than once in the book that your two loves at that point were meditation, farming and animals and there's a lovely example you gave, one point you had to sell your farm and you were quite sad about that and you were just sitting, feeling it and this ram came over to you. Just talk us through what happened there.

John: Excuse me, may I just jump back for a moment to make a little comment about that decision about meditation?

Iain: Of course.

John: The accusation is often made that meditation is a withdrawal from this world but absolutely on the contrary, the key principle of the method that I taught was that you practise it while living in the world. A monk's life may possibly be considered a withdrawal from worldly life but meditation, absolutely not. It is the art of finding the eternal, in the midst of the marketplace, the stillness in the movement.

Iain: To be, I forget the exact phrase, but *to be in the world but not of the world.*

John: Absolutely, that's the good phrase *in the world but not of the world.* Yes.

Iain: I understand that.

John: Yes, and it is utterly practical. It is absolutely not a withdrawal, an opting out, it is a completely different understanding.

Iain: I have read many things over the years about monks that have spent years meditating in very confined places, like a cave or a monastery and they come to the city and they are lost.

John: Yes.

Iain: And what you're saying is that, that stillness, that presence it's right in the marketplace, in the city.

John: Yes, in the most chaotic imaginable situation. Yes.

Iain: Yes.

John: God is with us.

Iain: Yes. I am going to insist on the story about the ram because I love the story.

John: Yes, so do I [laughs]. I think it is one of those wonderful things that I have got no explanation for but at that time...one of the great loves of my life are sheep...I can tell you a lot about my understanding of the *lamb of God* [laughs] anyway, at that time I had quite a considerable flock of sheep; about one hundred and fifty sheep, and five rams I think and one of these rams was an old warrior, where through much fighting he'd split his skull and was...old soldier [laughs]. And just before things happened; I had to move on from my first farm. I was sitting on one side of the field, I'm not sure if I'd been crying, but I was very unhappy about it all, losing my beloved animals and these rams were lying under a hedge at the other side of the field about, I suppose, a hundred yards or so away. And to my amazement, one of these rams; this old warrior, he stood up, he left the others, slowly and deliberately he walked across the field, he laid his head in my lap and just stood there for a minute or two, or three. And he turned away and went back and laid back with his companions. It brings tears to my eyes to tell you. Well, what do you make of that?

Iain: That extraordinary connection that you have had with nature, which is everyone's potential in a way.

John: Well, maybe that was it. I did consider that [to be] one of the greatest honours of my life. I couldn't ask for more.

Iain: *One of the greatest honours of your life* [nodding]. Yes, wonderful.

John: See, [this] Russian heart brings tears to my eyes [wipes his eyes dry] even in front of a camera, I'm sorry.

Iain: Well, you have had a bit of an up-and-down story in some ways and I'm going to now move on because in your late forties, your life fell apart and you had quite bad depression. How did that start?

John: Well, I had a second farm then, it was a lovely little farm and that is really another little story. I was happy as a farmer, I was married by then and had a good wife...but we had many meditation students at that time who used to come to the farm. I was quite well known, as one of the first organic farmers. There was a woman that came to meditate and on one occasion...we meditate with closed eyes by the way...we were sitting together and we'd just come to stillness and I saw our two souls rise from our bodies and merge as one. She was a woman with very open clear eyes and when I looked at her, I saw right through to the infinite beyond.

Iain: So, what does that mean?

John: What does that mean?

Iain: The "infinite beyond." What did you actually see?

John: Well you have got to realise there are two sorts of sight; there's the eyes of flesh and there's what's called *insight*...seeing with the eyes of the heart. [smiles]. Flesh sight is always limited; it has a boundary, flesh sees flesh. But we all have to some extent a sense of indescribable beauty, or indescribable peace...something like that. What did I see? I saw the indescribable, right there. I saw the infinite indescribable. But it is the realest of the real when you see it. And what really tipped me back, tipped me into depression was that I was still a young man, a hot-blooded young man, still very much living in my physical body and my human emotion. How do you reconcile the two? There was that spiritual union, if you like, the mystical marriage, contrasted with two people living lives both with their own marriages, their homes, their jobs that were separate. How do you reconcile unity with separation? Well, I couldn't at that time. It was beyond my ability, my experience. I couldn't go back into that old life. Of course, I couldn't escape it either, really, I was sort of, imprisoned in it.

Iain: So it was an experience that took you out [raises arms in a wide arc above his head] of your world.

John: Yes, that's right. I suppose in modern jargon, it blew my mind. I'm not sure if that is accurate or not. It's not a phrase I normally use.

Iain: Sounds very accurate! It blew your mind [laughs]. 68

John: But, I went back home and there was my dear wife but somehow it was all too small, I couldn't...I had been shown something...well anyway, the gist of it was it threw me into a turmoil of emotions and I left. I had to really break away.

Iain: You had to leave your marriage.

John: I left my farm, I left my home.

Iain: Wow.

John: I had one of the little motor caravans of that time and I drifted around for some years homeless, jobless, loveless and alone. And it was a wretched time of life. I just picked through it, I did what I could.

Iain: But you'd had that experience. So, had that given you a reference point, had it given you an opening?

John: Yes it did because how can one access it? Well, meditation of course does just that. Because in meditation you...if I can give you a demonstration, the beautiful demonstration of meditation, I hope the camera can see my hands, is just that; [unfolds clenched fingers into open palms].

Iain: It's just an opening.

John: It's letting go.

Iain: letting go.

John: Now this is how we live [tightens fingers again], forgetting, forgetful of the One.

Iain: Trying to hold on.

John: ...trying to hold on. We hold on to our personal life and so we are imprisoned with our ego, which is our sense of separation. And in meditation, it starts very gently at first, so it is not frightening or anything but very gently it helps you to do that [unfolds fingers to open palms again]. Now when you let go, you discover that you are not actually separate at all. You are united. You are in that which is undivided. Indescribable but undivided. There's not two at all, there's just One. One love. One person. Singular. Adam in the paradise was singular, one I Am. Now that's what I had been shown in this dramatic episode with this woman; the Oneness. Well, you could say, that then the work, the real work began because the two polarities had been clearly identified to me. I was too muddled really to put it as clearly as I am saying to you now but that's what gradually dawned on me. At one time in the motor caravan I went to spend a winter in Spain, alone of course and I spent hour after hour after hour just meditating. I moved from doing the standard half-hour morning and night and meditation became salvation because in salvation you are taken out of this imprisonment and [unfolds ar ms] you are shown what's real. You're saved from drowning in this world, just like Saint Peter was walking on water; he was drowning in the world, [and] there was Jesus free beside him. Peter was drowning, he reached, he said, "help me." Jesus said "what were you frightened about? What were you drowning for? Have faith."

Iain: Have faith.

John: That's what it's all about.

Iain: And you never stopped having faith even though it was a difficult time?

John: I don't think I ever did because I had this wonderful practice and this practice [meditation] is such a wonderful way of putting it into practice. So twice every day without fail and for increasing lengths of time. I was just surrendering to that total presence and to that love that has no end. That love that never says no. To pure, total love which is, which I'd seen in her eyes you see? And yet the body of course said no...

Iain: ...in a way it wasn't to do with *her*...

John: ...well...

Iain: ...she was a portal somehow...

John: well the body was a portal because that isn't really what we are. And this is the great discovery; that man is not limited to the flesh, the flesh as the Bible tells us is prophet of nothing.

Iain: Yes.

John: The flesh is just...look, anything that dies, mortality, the whole world [that] comes to pass is not what we are. Man, is eternal being.

Iain: Okay. I am going to go back to your story a little bit because I think it is important for people to see that your path wasn't always smooth, it had ups and downs, and how you dealt with the downs I think is so important and people somehow, they get stuck in having the highs, as they see them; the experiences but these practicalities.

John: Yes of course, well, it's discipline that pulls you through. You have just got to keep on practising. Practise, practise, practise.

Iain: This discipline, in the motor-home, you kept the discipline of meditation.

John: Yes, but in a way, it isn't difficult because it is a way, in a way it is like, well it is being described as a trail of grains of sugar, you know? You follow it because it's always leading you from better, to better, to better.

Iain: From better, to better, to better.

John: Yes, it's described as a trail of sugar, you see, leading to the sugar mountain, which is of course the Kingdom of God.

Iain: Yes but unfortunately in our society there's so many false trails, trying to take you from better, to better, to better and all you end up with is an unhealthy body and an overdraft and credit card bills [laughs] and...

John: Well that's why it's...well I think one of the impediments, one of the things that stops us setting out on the spiritual life is that we are not sufficiently unhappy. We are too content with this sort of compromise with life, with all the little sandwich bars and 71 baubles that life offers to us; that comfort of a teddy bear and you know for some people that's not good enough, you want more, you want the real thing. And I guess I was one of those people.

Iain: Yes but you also had what I would call, the taste, not the taste, as it is not a strong enough word but you had visions, in one way, you had big, big, clues and not everyone has that.

John: Well yes, that's also true and am I not blessed?

Iain: There is a blessing in that, you are absolutely right.

John: Absolutely, you know they say, the Bible tells us we are saved by grace. What is grace? It is something that comes unseen, unknown, you know, it is like memory, where does memory come from? It just comes, doesn't it?

Iain: I think what we are going to do is a part two of this interview because we have about ten minutes left and I am only...so we will keep going and there will be a part two. So, what happened next was in 1998 you went to Africa for a time.

John: Yes, I was offered a job out in Africa, South Africa. I went out there, the job didn't work out, so after some time I hired a little car and I just drove off. I didn't really have a plan, I didn't really have a proper map but I just followed the road and it all unfolded in front of me. I slept in the back of the car or out on the ground under the stars, oh I actually loved it. The space, the glorious space. And I never went to any big towns only little ones, I just bought what I had to and got out into the open again [laughs]. I just found the big empty spaces on the map and I went there.

Iain: It comes across in the book that you are always drawn to wide-open, preferably wild places.

John: Yes.

Iain: and but for the wind there was [were] utter silences that you'd never known before.

John: Yes.

Iain: There was no place for your depression anymore.

John: No, I suppose, out there...I was so thrilled by it, so...

Iain: Utter silence.

John: Yes, so I just couldn't get enough of space and silence. I have always loved space and silence, they're just natural to me, I belong there. That's where I feel at home.

Iain: But it seems to me that it is kind of, what you've told us so far about your life, it's almost like there is this dance of space and you are drawn to this space on the outside, you recognise the real space is primarily on the inside. And you are in Africa and of course you are completely attracted to the stillness of the space, nothing around for miles and miles.

John: Yes, I actually loved that. When I was a boy at school, my favourite picture was of a cowboy riding up to the crest of a hill with the caption "don't fence me in" I loved that phrase. And Africa was in that sense...yes and then I went on, I was in the Kalahari and the Namibian desert and that...oh I just loved it. It always seemed to me [to be] obvious why the early Christians, why men of prayer went to the desert and I experienced it for myself and it is just all so obvious there, it is all just before you; the Infinite. You are nothing. You are taken into the immensity of what's there.

Iain: Because you talk in the book about there, when you are in Africa about the absence of subject/object relationships. It's not you and the other, it's just the One.

John: No, that's right. All that dies away. All the personality is, is nothing.

Iain: Yes.

John: The 'me', the John Butler is just...you forget about it...it's just nothing.

Iain: Yes, and of course you came back from Africa to England...

John: Yes, [laughs] where you can imagine that is the opposite, getting back to [England]...well I'd get back into John Butler again [laughs]. Or what the world considered that to be.

Iain: And you found it tough again, didn't you?

John: Well, I, you know, I had lost my job as a farmer. I was desperate to find some sort of work and what on earth could I do? I wrote a CV [curriculum vitae] at that time and I remember more-or-less what I wrote. I wrote I knew something about freedom and therefore I could help others to freedom. And of course, freedom is love. Love is freedom. The two are really the same thing, spiritually speaking. And if someone could give me a channel for my love, I would give my all. That was what I was looking for. And of course, who answered my CV? Nobody [laughs]! I was looking for freedom in the world of bondage.

Iain: But you'd also had the realisations before when you were in London and you saw the garbage as beautiful in the underground [tube station] and somehow, you'd had those experiences but something...it is hard isn't it? I'm just pointing out that you had had these reference points but you had this openness in Africa, this stillness. John Butler has almost disappeared and you get back to England, and the reality of day-to-day life hits you again.

John: Well, I suppose, I hadn't...I was still...we are such spiritual infants, you know, even now as an old man I am still a spiritual child. It's a long journey and one is learning all the time. You learn something every day. And at that time, I was still grappling with questions that I, that now, I no longer have these problems. But at that time, I did.

Iain: I just wanted people to understand where you really were. You said again, [that] you fell into personal desire. You had to deal with what you call *the cancerous root of egoism* by exposing it bit-by-bit. How did you expose it bit-by-bit? The cancerous root of egoism.

John: Yes, that's a good phrase [laughs]. How did I deal with it? Well, how indeed. I'm not sure that *we* can deal with it because you see *we*, *I* am the ego, so it is the ego trying to deal with the ego. It's the pot calling the kettle black. The blind leading the blind. We are saved by grace. Well, I meditated. At that time, I met a teacher, a young man and I looked into his eyes and I had that same experience of seeing the infinite beyond.

Iain: That you'd had with that woman.

John: Freedom, yes. And I followed him out to America, to San Francisco. I was that desperate. I knew that's what I wanted, I didn't want anything else. So, as it were, I jumped off the precipice to him and while I was in America after I had been with him a few days...I remember it was a big meeting, and he looked at me and he pointed out my pride, my arrogance and my egoism, which completely crushed me. I was exposed in this room of, I suppose, a couple of hundred people. I'd been called in the room and I felt within me a monstrous, almost like a worm and I didn't know what to do with it at all. I was absolutely terrified, and I fled. Where did I flee to? I fled into the wilderness. I got a car and I just drove into the desert. And I thought I was going mad at that time. I had such a sense of evil within me and I didn't know how to deal with it at all. I meditated but somehow even meditation didn't deal with it and fearing I was really going to lose my wits [mind/ability to think] I took a job as a cook in a funny little motel/gas station, I worked in the kitchen there, frying eggs and things...and it was in the Maharvi desert, which is just on the border of Arizona. Surrounded by desert-country. One day after work, I walked up the side of the valley, there was this little motel, this little spot at the side of the valley, I sat on a rock and I think I put my head in my hands and I think I just was finished then. And someone came and stood beside me. I didn't see anybody, I didn't hear anybody, no man was involved at all but I felt there was a presence beside me. I suppose it was Jesus. I never doubted it. It was nothing to do with the church, nothing to do with religion at all. And I didn't really notice any difference, the depression didn't end but I wrote a poem, that's right "depression didn't end but from then on I had a friend." I certainly didn't have any human friend at that time. And then a few more months passed and I ended this job with a pocket full of money, so once more I hired a car and had a wonderful time exploring the western states, the cowboy country and more 75 animals and more beloved prairie, then I came home and once again in this awful abyss of not knowing what to do.

Iain: I just want to...so, we have to finish...let's call this part one...so what the breakthrough was for you was the appearance of what you felt might have been, could be Jesus. It was about having a companion, a friend, a support, a guide...am I using the right words?

John: I think you are making too much of it. I wouldn't use any of those words, it was less defined. It was very undefined. Soon after I got back, I had some friends then that did healing and I remember they prayed over me and it was extraordinary, I felt like, I found myself screaming, I was thrown into the ground and something was expelled, some revolting thing came out of my mouth, it opened my mouth so wide that my mouth split but what came out? I never saw it. I suppose, one idea expelled by another. And just before that happened, I had gone into a job centre and I was invited to an open day and I was invited to go to Nottingham University to study Russian as a very mature student.

Iain: Okay, we're going to stop there because that's a great start for part two. So, thank you very much for doing part one. Thank you everyone for watching part one, here with John and we will see you again for part two.

Appendix D: GME Script

WHEN the phone rang, the gray-haired man asked the girl, if she would rather for any reason he didn't answer it. The girl heard him as if from a distance, and turned her face toward him. The grayhaired man asked her to hurry up, and she raised up on her right forearm just quickly enough so that the movement didn't quite look perfunctory. She cleared her hair back from her forehead with her left hand and said, "God. I don't know. I mean what do you think?" The gray-haired man said he didn't see that it made a helluva lot of difference one way or the other. He reached for the phone with his right hand. "Hello?" he said resonantly into the phone. The girl stayed propped up on her forearm and watched him.

A man's voice — stone dead, yet somehow rudely, almost obscenely quickened for the occasion — came through at the other end: "Lee? I wake you?"

The gray-haired man glanced briefly left, at the girl. "Who's that?" he asked. "Arthur?"

"Yeah — I wake you?"

"No, no. I'm in bed, reading. Anything wrong?"

"The reason I called, Lee, did you happen to notice when Joanie was leaving? Did you happen to notice if she left with the Ellenbogens, by any chance?"

"No, I didn't, Arthur," he said. "Didn't she leave with you?"

"No. Christ. You didn't see her leave at all, then?"

"Well, no, as a matter of fact, I didn't, Arthur. Why? What's up? Joanie lost?"

"Oh, Christ. Who knows? I don't know. You know her when she gets all tanked up and rarin' to go. I don't know. She may have just — "

"You call the Ellenbogens?" the gray-haired man asked.

"Yeah. They're not home yet. I don't know. Christ, I'm not even sure she left with them. I know one thing. I know one goddam thing. I'm through beating my brains out. I mean it. I really mean it this time. I'm through. Five years. Christ."

"All right, Arthur," the gray-haired man said. "In the first place, if I know the Ellenbogens, they probably all hopped in a cab and went down to the Village for a couple of hours. All three of 'em'll probably barge — "

"I have a feeling she went to work on some bastard in the kitchen. I just have a feeling. She always starts necking some bastard in the kitchen when she gets tanked up. I'm through. I swear to God I mean it this time. Five goddam-"

"Where are you now, Arthur?" the gray-haired man asked. "Home?"

"Yeah. Home."

"Well, just try to take it a little — What are ya — drunk, or what?"

"I don't know. How the hell do I know?"

"All right, now, listen. Relax. Just relax," the grayhaired man said. "You know the Ellenbogens, for Chrissake. What probably happened, they probably missed their last train. All three of 'em'll probably barge in on you any minute, full of witty, night-club — "

"They drove in."

"How do you know?"

"Their baby-sitter. We've had some scintillating goddam conversations. We're close as hell. We're like two goddam peas in a pod."

"All right. All right. So what? Will ya sit tight and relax, now?" said the gray-haired man. "All three of 'em'll probably waltz in on you any minute. Take my word. You know Leona. I don't know what the hell it is — they all get this god-awful Connecticut gaiety when they get in to New York. You know that."

"Yeah. I know. I know. I don't know, though."

"Certainly you do. Use your imagination. The two of 'em probably dragged Joanie bodily — "

"Listen. Nobody ever has to drag Joanie anywhere. Don't gimme any of that dragging stuff."

"Nobody's giving you any dragging stuff, Arthur," the gray-haired man said quietly.

"I know, I know! Excuse me. Christ, I'm losing my mind. Honest to God, you sure I didn't wake you?"

"I'd tell you if you had, Arthur," the gray-haired man said. Absently, he took his left hand out from between the girl's upper arm and chest wall. "Look, Arthur. You want my advice?" he said. He took the telephone cord between his fingers, just under the transmitter. "I mean this, now. You want some advice?"

"Yeah. I don't know. Christ, I'm keeping you up. Why don't I just go cut my — "

"Listen to me a minute," the gray-haired man said. "First — I mean this, now — get in bed and relax. Make yourself a nice, big nightcap, and get under the — "

"Nightcap! Are you kidding? Christ, I've killed about a quart in the last two goddam hours. Nightcap! I'm so plastered now I can hardly — "

"All right. All right. Get in bed, then," the grayhaired man said. "And relax — ya hear me? Tell the truth. Is it going to do any good to sit around and stew?"

"Yeah, I know. I wouldn't even worry, for Chrissake, but you can't trust her! I swear to God. I swear to God you can't. You can trust her about as far as you can throw a — I don't know what. Aaah, what's the use? I'm losing my goddam mind."

"All right. Forget it, now. Forget it, now. Will ya do me a favor and try to put the whole thing out of your mind?" the gray-haired man said. "For all you know, you're making — I honestly think you're making a mountain — "

"You know what I do? You know what I do?

I'm ashameda tell ya, but you know what I very nearly goddam do every night? When I get home? You want to know?"

"Arthur, listen, this isn't — -"

"Wait a second — I'll tell ya, God damn it. I practically have to keep myself from opening every goddam closet door in the apartment — I swear to God. Every night I come home, I half expect to find a bunch of bastards hiding all over the place. Elevator boys. Delivery boys. Cops — "

"All right. All right. Let's try to take it a little easy, Arthur," the gray-haired man said. He glanced abruptly to his right, where a cigarette, lighted some time earlier in the evening, was balanced on an ashtray. It obviously had gone out, though, and he didn't pick it up. "In the first place," he said into the phone, "I've told you many, many times, Arthur, that's exactly where you make your biggest mistake. You know what you do? Would you like me to tell you what you do? You go out of your way — I mean this, now — you actually go out of your way to torture yourself. As a matter of fact, you actually inspire Joanie-" He broke off. "You're bloody lucky she's a wonderful kid. I mean it. You give that kid absolutely no credit for having any good taste — or brains, for Chrissake, for that matter — "

"Brains! Are you kidding? She hasn't got any goddam brains! She's an animal!"

The gray-haired man, his nostrils dilating, appeared to take a fairly deep breath. "We're all animals," he said. "Basically, we're all animals."

"Like hell we are. I'm no goddam animal. I may be a stupid, fouled-up twentieth-century son of a bitch, but I'm no animal. Don't gimme that. I'm no animal."

"Look, Arthur. This isn't getting us — "

"Brains. Jesus, if you knew how funny that was. She thinks she's a goddam intellectual. That's the funny part, that's the hilarious part. She reads the theatrical page, and she watches television till she's practically blind — so she's an intellectual. You know who I'm married to? You want to know who I'm married to? I'm married to the greatest living undeveloped, undiscovered actress, novelist, psychoanalyst, and all-around goddam unappreciated celebrity-genius in New York. You didn't know that, didja? Christ, it's so funny I could cut my throat. Madame Bovary at Columbia Extension School. Madame — "

"Who?" asked the gray-haired man, sounding annoyed.

"Madame Bovary takes a course in Television Appreciation. God, if you knew how — "

"All right, all right. You realize this isn't getting us anyplace," the gray-haired man said. He turned and gave the girl a sign, with two fingers near his mouth, that he wanted a cigarette. "In the first place," he said, into the phone, "for a helluvan intelligent guy, you're about as tactless as it's humanly possible to be." He straightened his back so that the girl could reach behind him for the cigarettes. "I mean that. It shows up in your private life, it shows up in your — "

"Brains. Oh, God, that kills me! Christ almightyl Did you ever hear her describe anybody — some man, I mean? Sometime when you haven't anything to do, do me a favor and get her to describe some man for you. She describes every man she sees as `terribly attractive.' It can be the oldest, crummiest, greasiest —

"All right, Arthur," the gray-haired man said sharply. "This is getting us nowhere. But nowhere." He took a lighted cigarette from the girl. She had lit two. "Just incidentally," he said, exhaling smoke through his nostrils, "how'd you make out today?"

"What?"

"How'd you make out today?" the gray-haired man repeated. "How'd the case go?"

"Oh, Christ! I don't know. Lousy. About two minutes before I'm all set to start my summation, the attorney for the plaintiff, Lissberg, trots in this crazy chambermaid with a bunch of bedsheets as evidence — bedbug stains all over them. Christ!"

"So what happened? You lose?" asked the grayhaired man, taking another drag on his cigarette.

"You know who was on the bench? Mother Vittorio. What the hell that guy has against me, I'll never know. I can't even open my mouth and he jumps all over me. You can't reason with a guy like that. It's impossible."

The gray-haired man turned his head to see what the girl was doing. She had picked up the ashtray and was putting it between them. "You lose, then, or what?" he said into the phone.

"What?"

"I said, Did you lose?"

"Yeah. I was gonna tell you about it. I didn't get a chance at the party, with all the ruckus. You think Junior'll hit the ceiling? Not that I give a good goddam, but what do you think? Think he will?"

With his left hand, the gray-haired man shaped the ash of his cigarette on the rim of the ashtray. "I don't think he'll necessarily hit the ceiling, Arthur," he said quietly. "Chances are very much in favor, though, that he's not going to be overjoyed about it. You know how long we've handled those three bloody hotels? Old man Shanley hi mself started the whole — "

"I know, I know. Junior's told me about it at least fifty times. It's one of the most beautiful stories I ever heard in my life. All right, so I lost the goddam case. In the first place, it wasn't my fault. First, this lunatic Vittorio baits me all through the trial. Then this moron chambermaid starts passing out sheets full of bedbug — "

"Nobody's saying it's your fault, Arthur," the grayhaired man said. "You asked me if I thought Junior would hit the ceiling. I simply gave you an honest — "

"I know — I know that.... I don't know. What the hell. I may go back in the Army anyway. I tell you about that?"

The gray-haired man turned his head again toward the girl, perhaps to show her how forbearing, even stoic, his countenance was. But the girl missed seeing it. She had just overturned the ashtray with her knee and was rapidly, with her fingers, brushing the spilled ashes into a little pick-up pile; her eyes looked up at him a second too late. "No, you didn't, Arthur," he said into the phone.

"Yeah. I may. I don't know yet. I'm not crazy about the idea, naturally, and I won't go if I can possibly avoid it. But I may have to. I don't know. At least, it's oblivion. If they gimme back my little helmet and my big, fat desk and my nice, big mosquito net it might not — "

"I'd like to beat some sense into that head of yours, boy, that's what I'd like to do," the gray-haired man said. "For a helluvan — For a supposedly intelligent guy, you talk like an absolute child. And I say that in all sincerity. You let a bunch of minor little things snowball to an extent that they get so bloody paramount in your mind that you're absolutely unfit for any — "

"I shoulda left her. You know that? I should've gone through with it last summer, when I really had the ball rolling — you know that? You know why I didn't? You want to know why I didn't?"

"Arthur. For Chrissake. This is getting us exactly nowhere."

"Wait a second. Lemme tellya why! You want to know why I didn't? I can tellya exactly why. Because I felt sorry for her. That's the whole simple truth. I felt sorry for her."

"Well, I don't know. I mean that's out of my jurisdiction," the gray-haired man said. "It seems to me, though, that the one thing you seem to forget is that Joanie's a grown woman. I don't know, but it seems to me — "

"Grown woman! You crazy? She's a grown child, for Chrissake! Listen, I'll be shaving — listen to this — I'll be shaving, and all of a sudden she'll call me from way the hell the other end of the apartment. I'll go see what's the matter — right in the middle of shaving, lather all over my goddam face. You know what she'll want? She'll want to ask me if I think she has a good mind. I swear to God. She's pathetic, I tellya. I watch her when she's asleep, and I know what I'm talkin' about. Believe me."

"Well, that's something you know better than — I mean that's out of my jurisdiction," the gray-haired man said. "The point is, God damn it, you don't do anything at all constructive to — "

"We're mismated, that's all. That's the whole simple story. We're just mismated as hell. You know what she needs? She needs some big silent bastard to just walk over once in a while and knock her out cold — then go back and finish reading his paper. That's what she needs. I'm too goddam weak for her. I knew it when we got married — I swear to God I did. I mean you're a smart bastard, you've never been married, but every now and then, before anybody gets married, they get these flashes of what it's going to be like after they're married. I ignored 'em. I ignored all my goddam flashes. I'm weak. That's the whole thing in a nutshell."

"You're not weak. You just don't use your head," the gray-haired man said, accepting a freshly lighted cigarette from the girl.

"Certainly I'm weak! Certainly I'm weak! God damn it, I know whether I'm weak or not! If I weren't weak, you don't think I'd've let everything get all — Aah, what's the usea talking? Certainly I'm weak ... God, I'm keeping you awake all night. Why don't you hang the hell up on me? I mean it. Hang up on me."

"I'm not going to hang up on you, Arthur. I'd like to help you, if it's humanly possible," the gray-haired man said. "Actually, you're your own worst — "

"She doesn't respect me. She doesn't even love me, for God's sake. Basically — in the last analysis — I don't love her any more, either. I don't know. I do and I don't. It varies. It fluctuates. Christ! Every time I get all set to put my foot down, we have dinner out, for some reason, and I meet her somewhere and she comes in with these goddam white gloves on or something. I don't know. Or I start thinking about the first time we drove up to New Haven for the Princeton game. We had a flat right after we got off the Parkway, and it was cold as hell, and she held the flashlight while I fixed the goddam thing — You know what I mean. I don't know. Or I start thinking about — Christ, it's embarrassing — I start thinking about this goddam poem I sent her when we first started goin' around together. `Rose my color is. and white, Pretty mouth and green my eyes.' Christ, it's embarrassing — it used to remind me of her. She doesn't have green eyes — she has eyes like goddam sea shells, for Chrissake — but it reminded me anyway ... I don't know. What's the usea talking? I'm losing my mind. Hang up on me, why don't you? I mean it."

The gray-haired man cleared his throat and said, "I have no intention of hanging up on you, Arthur. There's just one — "

"She bought me a suit once. With her own money. I tell you about that?"

"No, I — "

"She just went into I think Tripler's and bought it. I didn't even go with her. I mean she has some goddam nice traits. The funny thing was it wasn't a bad fit. I just had to have it taken in a little bit around the seat — the pants — and the length. I mean she has some goddam nice traits."

The gray-haired man listened another moment.

Then, abruptly, he turned toward the girl. The look he gave her, though only glancing, fully informed her what was suddenly going on at the other end of the phone. "Now, Arthur. Listen. That isn't going to do any good," he said into the phone. "That isn't going to do any good. I mean it. Now, listen. I say this in all sincerity. Willya get undressed and get in bed, like a good guy? And relax? Joanie'll probably be there in about two minutes. You don't want her to see you like that, do ya? The bloody Ellenbogens'll probably barge in with her. You don't want the whole bunch of 'em to see you like that, do ya?" He listened. "Arthur? You hear me?"

"God, I'm keeping you awake all night. Everything I do, I — "

"You're not keeping me awake all night," the grayhaired man said. "Don't even think of that. I've already told you, I've been averaging about four hours' sleep a night. What I would like to do, though, if it's at all humanly possible, I'd like to help you, boy." He listened. "Arthur? You there?"

"Yeah. I'm here. Listen. I've kept you awake all night anyway. Could I come over to your place for a drink? Wouldja mind?"

The gray-haired man straightened his back and placed the flat of his free hand on the top of his head, and said, "Now, do you mean?"

"Yeah. I mean if it's all right with you. I'll only stay a minute. I'd just like to sit down somewhere and — I don't know. Would it be all right?"

"Yeah, but the point is I don't think you should, Arthur," the gray-haired man said, lowering his hand from his head. "I mean you're more than welcome to come, but I honestly think you should just sit tight and relax till Joanie waltzes in. I honestly do. What you want to be, you want to be right there on the spot when she waltzes in. Am I right, or not?"

"Yeah. I don't know. I swear to God, I don't know."

"Well, I do, I honestly do," the gray-haired man said. "Look. Why don't you hop in bed now, and relax, and then later, if you feel like it, give me a ring. I mean if you feel like talking. And don't worry. That's the main thing. Hear me? Willya do that now?"

"All right."

The gray-haired man continued for a moment to hold the phone to his ear, then lowered it into its cradle.

"What did he say?" the girl immediately asked him. He picked his cigarette out of the ashtray — that is, selected it from an accumulation of smoked and halfsmoked cigarettes. He dragged on it and said, "He wanted to come over here for a drink."

"God! What'd you say?" said the girl.

"You heard me," the gray-haired man said, and looked at her. "You could hear me. Couldn't you?" He squashed out his cigarette.

"You were wonderful. Absolutely marvellous," the girl said, watching him. "God, I feel like a dog!"

"Well," the gray-haired man said, "it's a tough situation. I don't know how marvellous I was."

"You were. You were wonderful," the girl said. "I'm limp. I'm absolutely limp. Look at me!"

The gray-haired man looked at her. "Well, actually, it's an impossible situation," he said. "I mean the whole thing's so fantastic it isn't even — "
"Darling- Excuse me," the girl said quickly, and leaned forward. "I think you're on fire." She gave the back of his hand a short, brisk, brushing stroke with the flats of her fingers. "No. It was just an ash." She leaned back. "No, you were marvellous," she said. "God, I feel like an absolute dog!"

"Well, it's a very, very tough situation. The guy's obviously going through absolute — "

The phone suddenly rang.

The gray-haired man said "Christ!" but picked it up before the second ring. "Hello?" he said into it.

"Lee? Were you asleep?"

"No, no."

"Listen, I just thought you'd want to know. Joanie just barged in."

"What?" said the gray-haired man, and bridged his left hand over his eyes, though the light was behind him.

"Yeah. She just barged in. About ten seconds after I spoke to you. I just thought I'd give you a ring while she's in the john. Listen, thanks a million, Lee. I mean it — you know what I mean. You weren't asleep, were ya?"

"No, no. I was just — No, no," the gray-haired man said, leaving his fingers bridged over his eyes. He cleared his throat.

"Yeah. What happened was, apparently Leona got stinking and then had a goddam crying jag, and Bob wanted Joanie to go out and grab a drink with them somewhere and iron the thing out. I don't know. You know. Very involved. Anyway, so she's home. What a rat race. Honest to God, I think it's this goddam New York. What I think maybe we'll do, if everything goes along all right, we'll get ourselves a little place in Connecticut maybe. Not too far out, necessarily, but far enough that we can lead a normal goddam life. I mean she's crazy about plants and all that stuff. She'd probably go mad if she had her own goddam garden and stuff. Know what I mean? I mean — except you — who do we know in New York except a bunch of neurotics? It's bound to undermine even a normal person sooner or later. Know what I mean?"

The gray-haired man didn't give an answer. His eyes, behind the bridge of his hand, were closed. "Anyway, I'm gonna talk to her about it tonight. Or tomorrow, maybe. She's still a little under the weather. I mean she's a helluva good kid basically, and if we have a chance to straighten ourselves out a little bit, we'd be goddam stupid not to at least have a go at it. While I'm at it, I'm also gonna try to straighten out this lousy bedbug mess, too.

I've been thinking. I was just wondering, Lee. You think if I went in and talked to Junior personally, I could — "

"Arthur, if you don't mind, I'd appreciate — "

"I mean I don't want you to think I just called you back or anything because I'm worried about my goddam job or anything. I'm not. I mean basically, for Chrissake, I couldn't care less. I just thought if I could straighten Junior out without beating my brains out, I'd be a goddam fool — "

"Listen, Arthur," the gray-haired man interrupted, taking his hand away from his face, "I have a helluva headache all of a sudden. I don't know where I got the bloody thing from. You mind if we cut this short? I'll talk to you in the morning — all right?" He listened for another moment, then hung up.

Again the girl immediately spoke to him, but he didn't answer her. He picked a burning cigarette — the girl's — out of the ashtray and started to bring it to his mouth, but it slipped out of his fingers. The girl tried to help him retrieve it before anything was burned, but he told her to just sit still, for Chrissake, and she pulled back her hand.

Appendix E: Adult Participant Information Sheet

ADULT PARTICIPANT INFORMATION SHEET

Subject Code: ________________________ Birth date: ________________________ Sex:______

Do you consider yourself: ☐ right-handed ☐ left-handed ☐ ambidextrous

LANGUAGE BACKGROUND

Is English the first language that you learned? ☐ yes ☐ no

If *No*, what language did you first learn?______________________________

If *No*, at what age did you first begin learning English?______________________________

In what context?______________________________

If *No,* in which language (English or your native language) are you more comfortable?_________

Are you fluent in any language other than English? ☐ yes (list language),______________ ☐ no

Are you regularly exposed to any language other than English? ☐ yes,________________ ☐ no

If *Yes*, in what context? ______________________________

Are there are other languages not asked about above that you know? ☐ yes,_________________ ☐ no

If *Yes*, please list and describe how you learned them. ______________________________

____

____

What is your field of study/major? ______________________________

NEUROLOGICAL HISTORY

Have you ever had brain surgery? ☐ yes ☐ no

Have you ever had, or do you currently have, any neurological disorders (e.g., seizures, schizophrenia)?

☐ yes ☐ no If *Yes*, please explain: ______________________________

Are there any known neurological problems in your family? ☐ yes ☐ no

If *Yes*, please explain: ______________________________

Are you currently taking any medication(s) that may affect brain functioning (including but not limited to anti-depressants, anti-psychotics, anti-seizure)? ☐ yes,_____________ ☐ no

Have you ever had, or do you currently have, any speech, hearing, learning, or psychiatric disorders?

☐ yes ☐ no If *Yes*, please explain: ______________________________

VISION AND HEARING

Do you have normal or corrected-to-normal vision? ☐ yes ☐ no

Do you have normal hearing? ☐ yes ☐ no

CURRENT STATE

How many hours of sleep did you get last night? __________

How many hours of sleep do you typically get per night? __________

Do you feel like you got enough sleep last night to function normally both physically and mentally?

☐ yes ☐ no If no, please explain: ____

Is there any *other* circumstance (not asked about above) that makes you feel like you are not at your mental best right now? ☐ yes ☐ no If yes, please comment: ____________________________

Please rate your level of current fatigue on a 1-10 scale, where 1 is "so tired I can barely function today" and 10 is "I feel super rested, I've never felt better." (Circle 1-10)

(very tired) 1 2 3 4 5 6 7 8 9 10 (feel great)

Appendix F: Sleepiness and Fatigue Questionnaire

Participant ID_______________

How likely are you to doze off or fall asleep in the situations described below under normal circumstances?

Use the following scale to choose the most appropriate number for each situation:
0 = would never doze
1 = Slight chance of dozing
2 = Moderate chance of dozing
3 = High chance of dozing

Situation - **Chance of dozing**
Sitting and reading . . . . ______________
Watching TV . . . . ______________
Sitting, inactive in a public place (e.g. a theatre or a meeting) . . . . ______________
As a passenger in a car for an hour without a break . . . . ______________
Lying down to rest in the afternoon when circumstances permit . . .. ______________
Sitting and talking with someone . . . . ______________
Sitting quietly after a lunch without alcohol . . . . ______________
In a car, while stopped for a few minutes in traffic . . . . ______________

Please rate your current degree of sleepiness:

Pre-nap:

Degree of Sleepiness	Scale Rating
Feeling active, vital, alert, or wide awake	1
Functioning at high levels, but not at peak; able to concentrate	2
Awake, but relaxed; responsive but not fully alert	3
Somewhat foggy, let down	4
Foggy; losing interest in remaining awake; slowed down	5
Sleepy, woozy, fighting sleep; prefer to lie down	6
No longer fighting sleep, sleep onset soon; having dream-like thoughts	7
Asleep	X

Post-nap:

Degree of Sleepiness	Scale Rating
Feeling active, vital, alert, or wide awake	1
Functioning at high levels, but not at peak; able to concentrate	2
Awake, but relaxed; responsive but not fully alert	3

Somewhat foggy, let down	4
Foggy; losing interest in remaining awake; slowed down	5
Sleepy, woozy, fighting sleep; prefer to lie down	6
No longer fighting sleep, sleep onset soon; having dream-like thoughts	7
Asleep	X

Appendix G: Karolinska Sleep Log

KAROLINSKA SLEEP LOG

Participant ID: ____________
Date:___________________

1. At what time did you go to bed and turn the light off last night? ___________PM or AM
2. At what time did you arise this morning? ___________PM or AM
3. How long did you sleep? ___________hours and ___________minutes
4. How long did it take you to fall asleep? ___________hours and ___________minutes
5. How many awakenings did you have last night? ___________
6. How many total minutes were you awake after falling asleep last night? __________minutes

(Don't include time in bed before falling asleep)

7. Did you have any caffeine this morning? yes no If yes, describe quantity: ___________

Circle one per question only:

7. How did you sleep?

1	2	3	4	5
Very Poorly				Very Well

8. Did you feel refreshed after you arose this morning?

1	2	3	4	5
Not at all				Completely

9. Did you sleep soundly?

1	2	3	4	5
Very Restless				Very Soundly

10. Did you sleep throughout the time allotted for sleep?

1	2	3	4	5
Woke up much too early				Slept thru the night

11. How easy was it for you to wake up?

1	2	3	4	5
Very Easy				Very Difficult

12. How easy was it for you to fall asleep?

1	2	3	4	5
Very Easy				Very Difficult

13. How much did you dream last night?

1	2	3	4	5
None				Much

Appendix H: Karolinska Nap Log

KAROLINSKA SLEEP LOG
MODIFIED FOR AFTERNOON NAP

Participant ID: ___________
Date:___________________

1. How long did you nap for? ___________hours and ___________minutes
2. How long did it take you to fall asleep? ___________hours and ___________minutes
3. How many awakenings did you have during your nap? ___________
4. How many total minutes were you awake after falling asleep? __________minutes

(Don't include time in bed before falling asleep)

<u>Circle one per question only:</u>

5. How did you sleep?

1	2	3	4	5
Very Poorly				Very Well

6. Did you feel refreshed after woke up?

1	2	3	4	5
Not at all				Completely

7. Did you sleep soundly?

1	2	3	4	5
Very Restless				Very Soundly

8. Did you sleep throughout the time allotted for your nap?

1	2	3	4	5
Woke up after a short time				Slept for 90 min or more

9. How easy was it for you to wake up?

1	2	3	4	5
Very Easy				Very Difficult

10. How easy was it for you to fall asleep?

1	2	3	4	5
Very Easy				Very Difficult

11. How much did you dream during your nap?

1	2	3	4	5
None				Much

Appendix I: Post-Task Interview

Post-Task Interview

1. Did you notice anything interesting or unusual about the stimuli?

2. Did you notice any kind of pattern, structure or systematic relationship between the different stimuli or the different types of stimuli? If yes, please elaborate.

Appendix J: Debriefing Form

DEBRIEFING FORM

Project Title: Studies of sleep and language learning

Principal Investigator:
Dr. Laura Batterink

Thank you for your participation in this study. The purpose of this study was to examine how sleep contributes to the consolidation and retention of new linguistic information. Sleep has been shown to play an important role in memory consolidation, and also in the generalization and abstraction of hidden patterns or overarching rules in the environment. Our main hypothesis is that sleep contributes to the consolidation and strengthening of many different aspects of language, such as learning of sound patterns and vocabulary acquisition. We hypothesize that sleep may play an especially important role in generalization aspects of language learning, such as grammatical rule generalization. We are also interested in testing which—if any—aspects of language processing can occur during sleep, by assessing how the brain responds to different types of linguistic stimuli presented at non-awakening thresholds during sleep.

By having you complete different tasks, we were able to assess what you learned, consolidated, and retained about the language-related stimuli that you were presented with. We also recorded your brain activity to monitor how your brain responds to different types of stimuli, and how these brain responses relate to overall learning success. By recording your brain activity while you were given the opportunity to nap, we were also able to see how long you slept, and what stages of sleep you were in. Your data will help us understand how different sleep mechanisms contributes to memory consolidation in a language-learning context. Your participation and responses are much appreciated.

As part of this experiment, you may have been in an experimental condition in which auditory stimuli were presented at low volumes while you were asleep. We did not inform you about this possibility prior to your nap, because expecting that auditory sounds may be presented can make it more difficult to fall asleep, and may also lead to differences in processing the stimuli during sleep, potentially leading to greater likelihood of arousal. If this makes you uncomfortable you are free to withdraw your data from our sample.

If you would like to learn more, here are some interesting references on the role of sleep in memory consolidation and language:

- Schreiner, T., & Rasch, B. (2017). The beneficial role of memory reactivation for language learning during sleep: A review. *Brain and Language*, *167*, 94–105.

- Diekelmann, S., & Born, J. (2010). The memory function of sleep. *Nature Reviews Neuroscience,* 11, 114–126.

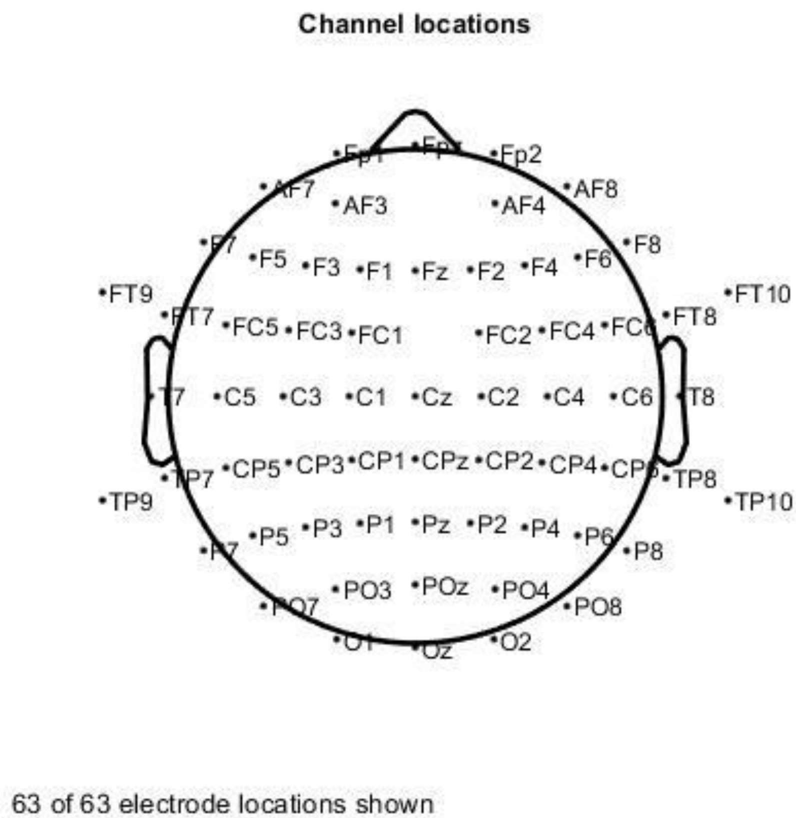
- Walker, M. P., & Stickgold, R. (2010). Overnight alchemy: Sleep-dependent memory evolution. *Nature Reviews Neuroscience*, 11, 218–219.

- O'Neill, J., Pleydell-Bouverie, B., Dupret, D., & Csicsvari, J. (2010). Play it again: Reactivation of waking experience and memory. *Trends in Neurosciences*, 33, 220–229.

Your results are confidential to the experimenters and all results are published anonymously as group data. If you have any further questions about this study please contact Sarah Hollywood or Dr. Laura Batterink

If you have questions about your rights as a research participant, please contact the Director of the Office of Research Ethics

Appendix K: Electrode Locations



Curriculum Vitae

Name:	Ashwin Harimohan
Post-secondary Education and Degrees:	Western University London, Ontario, Canada 2014-2018 B.Sc. Neuroscience
Related Work Experience	Teaching Assistant Western University 2019-2021
Poster Presentations	Cognitive Neuroscience Society Conference Understanding Neural Signals of Memory Consolidation During Sleep Virtual Conference 2021