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THE IMPACT OF TASK LOAD ON NEURAL ENTRAINMENT TO ATTENDED SPEECH: A DUAL-TASK MAGNETOENCEPHALOGRAPHY (MEG) PARADIGM

by

Michelle T. Kassel

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ABSTRACT

THE IMPACT OF TASK LOAD ON NEURAL ENTRAINMENT TO ATTENDED SPEECH: A DUAL-TASK MAGNETOENCEPHALOGRAPHY (MEG) PARADIGM

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Michelle T. Kassel

The University of Wisconsin – Milwaukee, 2020
Under the Supervision of Professor David Osmon, Ph.D.

Speech comprehension in a noisy environment requires active cognitive control mechanisms to select the relevant speech signal while filtering out irrelevant distractions. When processing speech in a multitask scenario, neural resources underlying cognitive control are considerably burdened and interfering information becomes more difficult to ignore. The present study utilized magnetoencephalography (MEG) to investigate the impact of multitasking on selective attention to speech. Twenty healthy adults performed a multitask paradigm with varying levels of both competing auditory distraction and concurrent visual working memory load. While increased visual working memory load was associated with reduced selective attention to speech in both the presence and absence of competing distraction, auditory distraction alone did not hamper accurate detection of the target speech. Under lower visual working memory load, left temporal regions entrained more strongly to attended speech in the absence of auditory distraction, while entrainment of right frontal structures emerged when selectively attending amid competing speech. At these lower levels of cognitive demand, entrainment to the attended speech occurred at latencies corresponding to temporal variations of the speech envelope (300-400 ms). In contrast, neural entrainment to ignored speech occurred at earlier latencies (~50 ms) and was evident in left parietal regions under lower working memory demands, as well as in left temporal cortex when compared to the attended speech steam. Taken together, the present findings provide evidence for both top-down neural enhancement and suppression mechanisms subserving selective attention to speech while multitasking. The present results further demonstrate that both mechanisms for neural enhancement and suppression are modulated by concurrent task load. Such findings provide a foundation for investigating impairments in cognitive control and selective attention to speech associated with normal aging and neurological disease.

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The Impact of Task Load on Neural Entrainment to Attended Speech:
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1. Introduction

Selective attention is a fundamental aspect of daily cognitive function, allowing humans to remain focused on a task in the presence of competing irrelevant distraction. Such goal-oriented cognitive control entails both *attending* to relevant stimuli and *ignoring* irrelevant stimuli in the service of achieving a desired goal. In the auditory domain, selective attention is critical for comprehending speech in a noisy environment. As such, a competing talker scenario known as the 'Cocktail Party' effect (Cherry, 1953) affords a rich method to assess selection of the relevant speech signal amid distracting noise and competing signals. Recent literature has begun to uncover the neural mechanisms employed to enhance attention to relevant speech; however, less is known about the neural underpinnings for suppressing irrelevant information. Additionally, knowledge is scarce regarding how the brain simultaneously manages competing information of varying degrees among other sensory domains while concurrently engaged in selectively attending to speech. The present study utilized magnetoencephalography (MEG) to measure brain activity during a bimodal dual-task paradigm with simultaneous auditory and visual task goals (Figure 1) in order to investigate whether increases in working memory load reduce both task performance and the level of neural synchrony to attended speech sounds.

Primary hypotheses for both behavioral and neural objectives are briefly outlined as follows: Behavioral performance on each of the dual tasks was expected to vary as a function of cognitive load, such that increased cognitive load would be associated with decreased overall performance. Secondly, it was hypothesized that performance on the dual tasks would be inversely related to one another, thereby displaying decreases in performance on one task as a consequence, or cost, of increased performance on the concurrent task. The neural objective sought to examine the entrainment, or phase-locking, of the MEG signal to the speech signal. Specifically, the neural hypotheses held that entrainment of the neural signal to the attended speech waveform (Figure 2) would be greater under reduced working memory load in both the *absence* and *presence* of competing speech. Greater neural synchrony to attended speech and stronger suppression of the ignored speech during reduced task load was also expected; however, it was hypothesized that the extent of difference between the neural synchrony to attended and to ignored speech would be reduced under the greatest cognitive load. Each of these objectives, their related hypotheses, and relevant background are discussed in greater detail below.

1.1. Top-down Cognitive Control

Central to the study objective is the notion that top-down mechanisms regulate selective attention to speech by enhancing relevant signals and suppressing noise. Broadly, top-down regulation of cognition is driven by voluntary, endogenous processes guided by *a priori* knowledge relating to expectations and current goals. Expectations bias attention toward information deemed relevant in the environment in order to allocate appropriate neural resources to process pertinent stimuli. Behaviorally relevant information is prioritized at the expense of competing information (Desimone & Duncan, 1995), the effects of which can sometimes be so robust that anomalous events may utterly escape awareness (Mack & Rock, 1998; Most et al., 2001; Simons & Chabris, 1999; Wood & Simons, 2017). Consistent with the view that momentary expectations control perceptual awareness, the phenomenon of categorical perception is demonstrated in that listeners' expectations resulted in erroneously classifying a phonemic stimulus within a discrete phoneme boundary when, in fact, the stimulus had been manipulated along a continuum (Liberman, 1957). Hence discrimination of phoneme boundaries was bound to previous linguistic knowledge of possible phoneme categories familiar to the listener. Similarly, applying top-down knowledge of linguistic structure (Kidd, Mason & Best, 2014), familiarity with a given language (Ding et al., 2016), and anticipation derived through surrounding context each significantly aid in the comprehension of speech (Smirnov et al., 2014). Additionally, extensive research in the visual modality has shown significant performance advantages of attentional cueing for target prediction suggesting that information to guide attention prepares sensory processing sites, ultimately improving execution of task goals (Posner, 1980; Kastner et al, 1999; Chawla, Rees & Friston, 1999; Giesbrecht et al., 2006; Esterman & Yantis, 2010; Puri, Wojciulik & Ranganath, 2009; Stokes et al., 2009). Together these findings lend additional support to prior work demonstrating that top-down signals influence the neural processing of perceptual information to accomplish a desired goal (Kastner et al., 1999; Corbetta & Shulman, 2002; Gazzaley et al., 2007; Bressler, et al., 2008).

Extensive research has found a distributed network of frontal, cingulate, and parietal regions that collaboratively regulate complex cognition (e.g., selective attention, working memory, set shifting) in multiple sensory modalities (Figure 3; Corbetta & Shulman, 2002; Corbetta et al., 2008; Dosenbach et al., 2007; Vincent et al., 2008; Power et al., 2011; Power & Petersen, 2013; Geerligs et al., 2014; Ptak, 2012; Sadaghiani & D'Esposito, 2015; Menon, 2015). Specifically, prefrontal, anterior cingulate, insular and posterior parietal regions have been identified as hubs for global cognitive control; some further suggest that the widely functionally connected fronto-cingulo-parietal network operates to flexibly shift among various neural networks based on momentary task goals when highly adaptive cognitive control is required (Cole et al., 2013; Cole, Laurent, & Stocco, 2013; Dosenbach et al., 2006; Niendam et al., 2012;

Cai et al., 2015; Seeley et al., 2007). As alluded to above, these top-down regions exert cognitive control in part by modulating activity in sensory cortices receiving perceptual input for further integration. As such, activity of the prefrontal cortex (PFC) has been shown to modulate attention-related activity in sensory, including auditory, cortex based on task goals (Gazzaley et al., 2007; Neelon et al., 2011; Barceló, Suwazono & Knight, 2000; Bressler, et al., 2008; Atiani et al., 2009).

Animal models of goal-oriented attention underscore the role of separate modulatory mechanisms to enhance and suppress the neural signal in primary auditory cortex based on behavioral relevance (Atiani et al., 2009; Fritz et al., 2005; Fritz et al., 2007; Otazu et al., 2009; Steinmetz, 2000; Schwartz & David, 2018). These effects can also be modulated by task demand (Atiani et al., 2009; Boudreau et al., 2006). In humans, during a visual paradigm wherein cognitive load was manipulated, Gazzaley and colleagues (2007) demonstrated that PFC connectivity to fusiform face gyrus was increased while connectivity to parahippocampal place area was reduced when participants were instructed to attend to faces and ignore scenes. Importantly, the opposite pattern of connectivity to PFC was displayed when attending to scenes and ignoring faces, together supporting the notion that PFC differentially recruits neural resources based on current goals. Recent studies employing event related potentials (ERP) and functional magnetic resonance imaging (fMRI) revealed modulation of auditory cortex by task load in response to task-irrelevant sounds (Sabri et al., 2014; Sabri et al., 2013). When perceptual load was modulated parametrically in a signal-detection task, ERP responses to task-irrelevant speech sounds were greater as perceptual demands increased. Similarly, effects of working memory load were observed in the same time interval, with higher load resulting in greater distractor response. Of note, the attended and ignored information were presented sequentially in these studies minimizing concurrent competition on attentional neural resources.

However, when cognitive load is considerably burdened, interfering information is more difficult to ignore, likely a consequence of extensive taxing of neural resources (Konstantinou et al., 2014). Increased activation of broad fronto-cingulo-parietal cognitive control regions corresponding to higher working memory demands has also been reported (Wager & Smith, 2003), including when working memory was manipulated during a divided attention task (Santangelo & Macaluso, 2013). Additional attentional demand incurred within a dual-task situation reflects a similar pattern of cognitive control network involvement with larger extension of activation (Vohn et al., 2007; Deprez et al., 2013). Dual-task scenarios require rapid switching between tasks, thereby increasing attentional demands and resulting in a task switching cost (Monsell, 2003) that may manifest as a reduction in performance in one task when the concurrent task performance increases. Management of multiple cognitive streams of information imparts greater demand on the limited resources of the cognitive control network (Merian, Kessler & Adi-Japha, 2008). Sites within the fronto-cingulo-parietal network have been identified in attentional switching (Serences et al., 2005; Serences & Yantis, 2007; Shulman et al., 2007; Shomstein, 2012; Chica et al., 2013), with medial frontal/cingulate regions activated during brief intervals when participants switched from one task to another (Rushworth et al., 2002). Furthermore, cingulate involvement was determined to be superordinate rather than simply related to individual responses (Rushworth et al., 2002), implying a task set regulation of perceptual cortices. This interpretation was evident in a recent multitask investigation showing further recruitment of sensory cortices presumed responsible for rendering stimulus representations when a working memory component was added to an already challenging dual-task paradigm (Deprez et al., 2013).

1.2. Selective Attention to Speech

For the purposes of this study, it is important to consider how attentional filters prioritize auditory perceptual information in sensory processing sites based on task goals. At a fundamental level, neurons in primary auditory cortex are known to fire in the presence of sound; the pattern of activity in auditory cortex will therefore bear some resemblance to that of the sound signal over time. It is also well established that specialized neurons in auditory cortex modulate their tuning curve to match that of particular sound features. For example, the firing rate of a neuron specialized to respond to a sound at 1000 Hz will be enhanced when exposed to such frequency, while those neurons attuned to different frequencies will be laterally inhibited suppressing their baseline firing levels, thereby increasing the signal to noise ratio (Zhao & Zhaoping, 2011). When selectively attending to a sound among competing noise, the brain must mechanistically separate various sound segments in order to select and process the behaviorally relevant sound. Different attentional filters for spectral (i.e. frequency), temporal, and spatial components of sound can be used to make predictions about which sounds hang together and about the origins of the sounds. Aside from language spoken, content conveyed, and comprehensibility, basic speech sounds are fundamentally complex in that distinct voices exhibit variations in sound features over time including timbre (perception of harmonics or spectral content), pitch (perception of fundamental frequency), volume (intensity or amplitude), and rhythm or melodic sensation (periodicity) (Rosen, 1992). Separation of sound features and designation to distinct sources is requisite for speech comprehension in noise. While these principle aspects of sound processing help to decode speech at a basic level, there can be significant spectral overlap among speakers, sounds can emanate from locations in very close proximity, contain similar loudness, and compete considerably for attention; yet humans are able to parse sound sources and selectively attend to speech with remarkable precision.

Posing an even greater challenge, spontaneous speech is in constant flux throughout a given speech stream. Top-down processes must engage selective attention based on relevant sound features attributed to the target speech stream. Furthermore, the complexity of speech content necessitates engagement of working memory processes to track and continuously update constructions of meaning during listening situations. These processes are also aided by top-down prediction, and indeed, significant overlap has been found among regions implicated in cognitive control and speech comprehension, particularly when comprehension is highly dependent on context (Smirnov et al., 2015). Speech comprehension even in the *absence* of noise requires employment of top-down processes and working memory circuitry; thus, in a competing talker scenario (i.e. Cocktail Party) when noise is present, additional burden is placed on neural processes to command top-down functions. Top-down processes in such a noisy situation bias attentional resources to appropriately select and process relevant speech streams while ignoring irrelevant distractor sounds. In line with the selective attention framework, speech comprehension in noise is thought to be accomplished by enhancing the sensory signal to relevant speech and attenuating/suppressing that of distraction (Horton, D'Zmura & Srinivasan, 2013; Kong, Mullangi & Ding, 2014; Kong, Somarowthu & Ding, 2015). A recent MEG paradigm revealed that priming listeners with a target sentence facilitated segregation of two speech streams from the same speaker, concluding the process was achieved by top-down suppression of auditory cortex to the non-target speech stream (Wang et al., 2018). While there is ample evidence for enhancement and suppression subserving selective attention broadly within multiple sensory modalities (Gazzaley et al., 2007; Schwartz & David, 2018; Da Costa et al., 2013; Gouws et al., 2014; Guerreiro et al., 2014; Seidl, Peelen, & Kastner, 2012; Couperus & Mangun, 2010; Atiani et al, 2009), less is known about how the underlying neural mechanisms operate for optimal selective attention to speech.

1.3. Neural Synchrony of Auditory Cortex to the Speech Envelope

As suggested above, top-down control for selective speech processing is accomplished in part by modulating auditory perceptual cortex (Keitel et al., 2017), though special considerations apply to the characterization and measurement of the complex speech signal. Prior work has profitably used the temporal envelope and fine structure of speech to relate brain activity to speech stimuli (Figure 4). The temporal envelope refers to the slow variations over time in spectral energy of the speech signal, while the temporal fine structure denotes more rapid oscillations with rate constrained near the center of a given frequency band (Rosen, 1992; Moore, 2008). Neurons in auditory cortex reliably fire in a manner that corresponds to variations in the temporal envelope of the speech signal (Abrams, Zecker & Kraus, 2008; Abrams, Zecker & Kraus, 2009; Kubanek et al., 2013; Aiken & Picton, 2008; Lou & Poeppel, 2007). This neural tracking is referred to as entrainment, or phase-locking, of the auditory cortex to the speech envelope, and degree of entrainment has been linked to speech comprehension (Ahissar et al., 2001; Lou & Poeppel, 2007; Peelle & Davis, 2012; Peelle, Gross, & Davis, 2013). Notably, comprehending speech requires processing of both the envelope and the fine structure, although each serves a distinct purpose. The speech envelope is the primary factor for comprehension when noise is relatively absent while the fine structure becomes more important in the presence of competing background noise (Bidelman, 2016; Moon & Hong, 2014; Ding, Chatterjee, & Simon, 2014), as in naturalistic settings (Rimmele et al., 2015). Prior knowledge of linguistic structure as well as familiarity with a given language also modulate the neural tracking of speech (Ding et al., 2016), further underscoring the important role of top-down processes in guiding neural entrainment.

In addition to spectral, temporal, and spatial information contained in speech sounds, parsing the hierarchical linguistic structure (e.g., syllables, words, phrases) poses an additional burden on neural substrates for speech stream selection and intelligibility (Ding et al., 2016). Importantly, different frequency bands relate to different hierarchical aspects of speech. Both discerned from the temporal envelope, entrainment in the theta band reflects the syllabic boundaries of speech while the delta band seems to index prosodic information (Ding, Chatterjee & Simon, 2014; Ding & Simon, 2012a; Ding & Simon, 2012b; Keital et al., 2016; Ding et al., 2016). Recent evidence displays distinct neural response peaks in auditory cortex to syllabic, phrasal, and sentence level distinctions (Ding et al., 2016).

In a cocktail party scenario in which multiple speech streams are vying for attention, the neural firing rate of auditory cortex becomes more strongly entrained, or synchronized, to the temporal envelope of attended speech sounds (Kerlin et al., 2010; Ding & Simon, 2012a; Ding & Simon, 2012b; Zion Golumbic et al, 2013). According to the "selective entrainment hypothesis," attention commands top-down endogenous processes to entrain sensory cortices to the temporal structure of the speech signal (Zion Golumbic et al, 2013). This entrainment likely enhances the cortical representation of the relevant attended speech in contrast to that of the ignored speech (Mesgarani and Chang, 2012; Zion Golumbic et al., 2013; Zion Golumbic et al., 2012). As neural firing patterns attune to delta and theta changes, the phase-locking to the attended speech waveform is enhanced (Ding, Chatterjee & Simon, 2014). The entrainment to the delta and theta oscillations, in turn, increases the baseline for excitatory firing of faster acting neurons to enhance perception of the fine structure of the speech waveform. This enhanced baseline increases the firing amplitudes during gamma bursts that are timed to the delta and theta waves at their peak, ultimately increasing the signal to the attended stream to promote better processing of the temporal fine structure of speech. Multi-electrode surface recordings showed that fluctuations of signal power in the high-gamma range (70-150 Hz) over auditory cortex are modulated by task-relevance, dissociating representations of attended and ignored information (Mesgarani and Chang, 2012). While emergent evidence demonstrates signal enhancement to relevant speech through greater entrainment, accounts of the neural mechanisms for suppression of irrelevant competing sounds are less developed. Recent work provides some evidence for a suppressive mechanism such that neural synchronization to the speech envelope of ignored information is inversely correlated (Horton, D'Zmura & Srinivasan, 2013; Kong, Mullangi & Ding, 2014; Kong, Somarowthu & Ding, 2015); however, Horton and colleagues (2013) note that while they found initial support for both enhancement of attended and suppression of ignored speech, whether there is one unique neural mechanism that accomplishes both types of entrainment simultaneously remains unclear.

1.4. Aims and Hypotheses

Comprehensive research on selective attention has established that endogenous attention guided by task goals mobilizes resources in the PFC and other cognitive control regions to enhance processing in sensory cortex to relevant information while suppressing the neural signal to distraction. In a cocktail party situation, perhaps the mechanism for effective neural enhancement and suppression of the appropriate stimuli entails active tracking of both attended and ignored speech streams. Further complicating the cocktail party scenario with the addition of a dual-task working memory component, the present study aims to examine the performance outcomes and neural impact when cognitive control resources become overloaded and are therefore compromised for effective neural tracking during selective attention to speech. Cross-correlating the MEG signal with the temporal envelope of speech (Figure 5) provides a method for investigating neural entrainment to distinct speech streams during selective attention to speech (Aiken & Picton, 2008).

Along with the novel addition of a concurrent cognitive load manipulation to the cocktail party paradigm, the present investigation sought further methodological improvements. While selective attention to speech is a well-researched area, how the underlying neural processes unfold in a more naturalistic procedure is lacking. For example, despite inclusion in many cocktail party paradigms in prior work, the current study did not include trials of repeated auditory stimuli, as the neural response to repeated stimuli is subject to repetition priming and thus may potentially produce a different neural response than that to purely novel stimuli. Repetition also changes attentional processes because a memory component is added. Segments from *Alice's Adventures in Wonderland* (Lewis Carroll, 1865) and *Through the Looking Glass and What Alice Found There* (Lewis Carroll, 1871) were chosen due to the convoluted and nonsensical nature of the content requiring greater active attention to follow the meaning of the passages, while appropriate grammar and syntax were maintained. Furthermore, the present task was designed to be sufficiently difficult to inspire significant attentional focus that needed to be sustained throughout the dual-task challenge, and afforded attentional manipulation of both visual and auditory domains. Additionally, binaural stimuli that included both attended and ignored information allowed for investigation of neural activity involved in processing these separate streams for successful selective attention to speech.

1.4.1. Task Overview

The present study investigated neural firing patterns to attended and ignored speech streams while participants were instructed to focus attention simultaneously on distinct auditory and visual tasks (Figure 1). In a dual-task paradigm, the level of difficulty and degree of competing distraction were manipulated in a 3 (auditory selective attention) by 2 (working memory load) design. In the primary experimental auditory selective attention condition, Cocktail Party, one speech passage was presented to the specified attend ear, while a distinct speech passage was simultaneously presented to the ignore ear. In the Single Speaker condition, one speech passage was presented to the attend ear with silence in the ignore ear to remove effects of competing speech distraction. During the Cocktail Party and Single Speaker auditory selective attention conditions, participants were instructed to make a button press each time the word “Alice” was detected in the attended passage only. The third auditory selective attention condition, Passive Listening, dichotically presented two speech passages as in the Cocktail Party condition to maintain comparable levels of acoustic energy; however, participants were instructed to simply listen passively to the stimuli without active attempts to detect “Alice” or other auditory events in either passage. While performing the auditory selective attention task, participants were simultaneously engaged in a visual working memory task. Participants were required to respond to shapes presented on the screen according to either a 1-back or 2-back rule. Each auditory selective attention condition was paired with each of the visual working memory conditions for a total of six conditions. In the dual-task paradigm, it was hypothesized that increased visual working memory load would result in both decreased performance and reduced neural entrainment (phase-locking) to the attended speech.

1.4.2. Behavioral Performance Hypotheses

Behavioral performance will differ as a function of cognitive load. Given that cognitive control processes are assumed to operate under the constraint of limited resources, it was hypothesized that reductions in performance accuracy would be apparent in conditions with greater cognitive load. Specifically, higher average accuracy in both visual working memory (n-back) and auditory selective attention (i.e., responses to "Alice" events detected in the attended passage) was expected in conditions with reduced cognitive load (visual 1-back, auditory Passive Listening) compared to increased cognitive load (visual 2-back, auditory Cocktail Party). A main effect of visual working memory load was thus predicted such that higher accuracy will be evident in the 1-back relative to the 2-back condition. Additionally, a main effect of auditory selective attention was hypothesized such that the Passive Listening condition would display the highest accuracy and the Cocktail Party condition would exhibit the lowest accuracy.

Performance in the visual working memory and auditory selective attention domains will be inversely related. Multitasking is currently characterized by rapid switching between task sets, rather than concurrent fluid attentional engagement throughout (Monsell, 2003). The hypothesis that dual task performance will be inversely related was assumed to represent the multitask cost of tracking multiple cognitive streams. Thus during a multitask paradigm, the allocation of attention between the visual and auditory components of the task are expected to fluctuate over time. Therefore, performance on the dual tasks will likely fluctuate as attention shifts between the competing streams of information being registered in perceptual cortex. Thus, in addition to computing average accuracy for each attentional modality separately by condition as in the initial hypothesis, it is important to examine the relative performance between the simultaneous attentional task modalities. In both the Single Speaker and Cocktail Party conditions, which require responses to the attended passage throughout the blocks, it was predicted that accuracy in the visual working memory task would be inversely related to accuracy in the auditory selective attention task. Such a pattern of performance would suggest a trade off in attention allocation within a particular domain at a given time. Thus, as performance increases in one domain, it is consequently reduced in the other domain. It was expected that this inverse relationship would be more pronounced in the most cognitively demanding task, the 2-back Cocktail Party condition, indicative of a higher trade off in accuracy by attention domain at a given moment.

1.4.3. Neural Synchrony to Speech Hypotheses

In the absence of competing speech stimuli, phase-locking of the neural signal to the attended speech envelope will be greater in the condition with lower visual working memory load. Due to the limited neural resources for top-down control of perceptual cortices, it was hypothesized that higher cognitive load occupying greater neural resources would degrade perceptual tracking of attended speech. Prior to investigating the effects of dual-task cognitive load on neural entrainment to both attended and ignored speech, the study aimed to establish the basic impact of cognitive load imposed by the visual working memory dual-task on solely attended speech in the absence of competing noise. The Single Speaker condition was ideal for such an inquiry as the participant hears only one speech stream with no competing noise, while simultaneously engaged in either the 1-back or 2-back visual working memory task. As there was no ignored speech stream or other auditory distraction in the Single Speaker condition, we could simply investigate the effects of increased task load on neural entrainment to attended speech. It was expected that the increased working memory load of a 2-back task would reduce the attentional resources available for neurons to optimally track the attended speech envelope, and thus exhibit lower cross-correlation values of neural firing patterns to the attended speech envelope relative to the 1-back condition.

In the presence of competing speech distraction, the difference in neural phase-locking to the speech envelope of the attended and ignored streams will vary by visual working memory load. When selectively attending to sound among competing noise, prior literature holds that top-down processing tunes the appropriate perceptual cortices to enhance neural firing to the relevant signal and suppress firing to the irrelevant competing noise. When limited neural resources must support both top-down modulation of sensory cortices for speech selection and monitor task set for successful execution of task goals, cognitive control resources likely become overloaded. As with the behavioral hypothesis that increased cognitive load would result in reduced performance, it was expected that the neural response to attended speech would also diminish under these highly demanding conditions. Within the Cocktail Party condition, an interaction was hypothesized between visual working memory load and neural entrainment to the attended and ignored speech streams. Specifically, the cross-correlation values of the neural entrainment to attended and ignored speech envelopes were expected to be closer in value at a given lag position in the 2-back relative to the 1-back condition. Planned comparisons of the simple effects were also expected to reveal the following three findings. (1) Within the 1-back condition, higher neural entrainment to the attended speech would be evident relative to the ignored speech. (2) When comparing neural entrainment to attended speech streams by visual working memory load, it was hypothesized that neural phase-locking to the attended speech would be lower in the 2-

back compared to 1-back condition. (3) Lastly, neural entrainment to ignored speech was expected to be more strongly suppressed in the 1-back relative to the 2-back condition. Taken together, such findings would suggest that when cognitive control resources are overburdened in the brain, top-down suppression of irrelevant distraction in auditory cortex is less effectively maintained.

2. Methods

2.1. Participants

Twenty right-handed monolingual English speakers between the ages of 18-40 years with at least 12 years of education were recruited via community advertisements, including online postings (e.g., Craigslist). An initial phone screen was conducted to ensure inclusion/exclusion criteria. Potential participants were excluded if they endorsed a history of neurological, psychiatric, or major medical conditions; history of head trauma or loss of consciousness; history or current substance use disorder; and contraindications for MRI and MEG (e.g., metal in the body, pacemakers, pregnancy, claustrophobia, large tattoos on upper body/neck/face). Participants who exhibited normal or corrected-to-normal visual acuity were included. Audiometric testing was conducted in a sound-proof testing booth to ensure normal hearing (audiometric thresholds ≤25 dB HL 500 - 4,000 Hz). No exclusions were made on the basis of race, ethnicity, or gender. The data from two participants were excluded from the analyses due to significant artifact in the MEG signal that was not successfully removed with pre-processing (tSSS). Only half of the data were recoverable from a third study participant, and an additional three participants had at least one block of data that was compromised, and thus were not included in the analyses. For simplicity, only the complete datasets from the 14 remaining participants were included in the MEG data analyses so that data from all participants included were equally represented across conditions. All participants were included in the behavioral data analyses.

2.2. Dual-Task Paradigm

While undergoing MEG, participants completed a cognitive control dual-task employing simultaneous presentation of auditory and visual stimuli, varying cognitive load by condition (Figure 1). In a 3x2 factorial design, speech segments from a narration of stories composed the three auditory selective attention manipulations, and basic shapes comprised the two visual working memory load conditions presented simultaneously with the auditory challenge. Two speakers representing voices of a man and a woman recorded speech passages in a sound-proof testing booth. The auditory stimuli consisted of narrated passages selected from *Alice in Wonderland* (man voice) and *Through the Looking Glass* (woman voice). Periods of silence greater than 300 ms were removed. The sound recordings were low-passed filtered (<4 KHz) and divided into blocks with an approximate duration of 50 seconds each (Attend $M = 49.7$ s, $SD = 0.5$ s; Ignore $M = 49.8$ s, $SD = 0.4$ s, $p = .710$). Sound intensity (root mean square) was equated across stimuli. An average of 5 “Alice” events occurred within each passage (Attend $M = 4.7$, $SD = 0.7$; Ignore $M = 4.8$, $SD = 0.7$, $p = .262$).

The dual-task paradigm was programmed to electronically present stimuli using the E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA). Presentation of all narrated passages was randomized among participants and within presentation of the following three conditions. In the Cocktail Party (CP) condition, two passages were presented simultaneously with explicit instruction toward an “attend” ear (e.g., right) and “ignore” ear (e.g., left).

Participants responded via button press every time the word “Alice” was detected in the attend ear, while ignoring the distractor “Alice” events in the ignore passage. In the Single Speaker (SS) condition, one passage was presented to the attend ear, while silence was presented in the ignore ear, thus reducing auditory distraction relative to the Cocktail Party condition. Similarly, participants responded by button press each time the word “Alice” was detected in the attend ear. Finally, the Passive Listening (PL) condition presented two passages simultaneously as in the Cocktail Party condition; however, participants were instructed to passively listen to the auditory stimuli. As participants were instructed not to explicitly attend to either passage, no responses to auditory stimuli (i.e., “Alice”) were requested, minimizing the need to monitor and detect stimuli in the auditory domain, while matching the acoustic energy of the Cocktail Party manipulation. Although the Single Speaker and Passive Listening conditions were not directly comparable, both served as separate control comparisons to the Cocktail Party manipulation. The Single Speaker condition functioned for performance comparison of the visual working memory load impact during auditory attentional engagement in the absence of auditory distraction. The Passive Listening condition effectively controlled for the absence of an explicit effortful need for attentional enhancement or suppression of auditory stimuli.

Meanwhile, participants simultaneously engaged in a visual working memory task consisting of either a 1-back or 2-back challenge. Five distinct solid black shapes were randomly presented on a white background with stimulus duration of 100 ms each and button response windows allowable for up to 2500 ms post-stimulus. A fixation cross was presented between each shape stimulus for 3000 ms. Visual working memory load was blocked and delivered pseudo-randomly within each run, adhering to the corresponding n-back rule for a given block. For each shape presentation, participants were required to make a 2-forced choice button press response to identify the presently viewed shape as either a match (i.e., press button 1) or non-match (i.e., press button 2) based on the pertinent n-back rule.

Each auditory selective attention condition (Cocktail Party, Single Speaker, Passive Listening) was paired with a visual working memory condition (1-back, 2-back), resulting in six total conditions. The six conditions were blocked and presented randomly within a given run. Six blocks were presented within each of 6 runs for a total of 36 blocks. All visual stimuli presented within a given block were programmed to onset and offset with the timing of the attended passage presentation for that block. While all participants were presented with the same auditory passages (36 attended and 24 ignored) over the course of the scan session, the order of presentation was randomized without repetition of passages throughout the entire task. Each trial was therefore novel to enhance ecological validity and to avoid measuring neural and behavioral responses to repeated information. Additionally, attended and ignored pairs of auditory passages were randomly assigned without replacement. Thus, each participant experienced a novel combination and order of auditory stimulus presentation within and across all conditions to mitigate potential order or pair effects. In order to encourage and verify attentional engagement to the designated attend passage, participants were prompted at the end of each block to identify which of two lists contained the correct characters that appeared in the attended passage. Additionally, both n-back and character list accuracy feedback for each block was displayed to encourage optimal participant performance throughout the scan session.

While prior work suggests that button responses to auditory stimuli can occur as rapidly as 200 ms post stimulus onset (Jain et al., 2015), the simultaneous demanding nature of the present dual-task paradigm may impact response latencies (Balasubramaniam et al., 2015). Thus, a window for reaction time values deemed as correct responses was computed based on the observed reaction times to “Alice” events detected in the sample of data from the condition with the lowest task demand that required responses to “Alice” events (Single Speaker 1-back). All reaction times either above the 95th (1870 ms) or below the 5th (473 ms) percentile cutoff values of the observed reaction time distribution were deemed as incorrect responses. Although less than 2% of responses were quicker than 406 ms, given the potential for button responses to auditory stimuli as quickly as 200 ms reported in the literature, the response window was widened to 200 ms to ensure all potential correct responses were captured in the analyses. Additionally, to account for potential variation in response latencies due to increases in cognitive demand in the 2-back and Cocktail Party conditions, the response window was further widened to include responses up to 2000 ms post-stimulus onset. Ultimately, the allowable window for correct responses was defined as 200-2000 ms post-stimulus onset. The same response window cutoffs were applied to calculate accuracy for all conditions requiring responses to “Alice” events.

2.3. Procedure

Written informed consent was obtained prior to participation in the study. Participants completed two study visits. During visit one, participants completed a hearing screen, a practice task, and underwent a one-hour MEG scan session (including scanner placement and setup) while performing the dual-task. Total time for participation in visit one was approximately four hours. Visit two consisted of structural MRI acquisition, with collection of T_1-SPGR and T_2-Cube images for co-registration with MEG data to maximize localization of neural activity. Including placement and the MRI scan session of approximately 30 minutes, total participation time for visit two was one hour.

2.3.1. Image Acquisition

MRI. Whole brain imaging was acquired on a 3T GE MR750 scanner (GE Medical Systems, Milwaukee, WI) using a 32-channel head coil. Participants viewed a fixation cross during image acquisition to aid in gaze fixation and minimize head motion. A 30 second localizer scan was initially acquired to optimize position of brain slice acquisition. High resolution T_1-weighted whole brain anatomical images were obtained using a 3-D spoiled gradient-echo sequence (SPGR) as a set of 204 sagittal slices (voxel dimensions = 1.0 mm × 1.0 mm × 1.0 mm; TR = 8.2 ms; TE = 3.2 ms; flip angle = 12°; matrix size = 256 x 256; FOV = 256 mm; slice thickness = 1.0 mm) for a total collection time of 11 minutes. Parameters for the subsequent acquisition of a sagittal T_2-Cube as a set of 204 slices include the following: voxel dimensions = 1.0 mm × 1.0 mm × 1.0 mm; TR = 2500 ms; TE = 70-75 ms; flip angle = 90°; matrix size = 256 x 256; FOV = 256 mm; slice thickness = 1.0 mm, for a total collection time of 8 minutes and 46 seconds.

MEG. The MEG data were acquired in a magnetically shielded room with a Neuromag VectorView system (Elekta-Neuromag Oy, Finland) with 306 sensors arranged in 102 triplets of 2 orthogonal planar gradiometers and 1 magnetometer. Before the experiment, a Polhemus Isotrak® system was used to digitize cardinal landmarks (i.e., nasion, left and right pre-auricular points) and head shape of at least 200 additional points from the head surface, with further points traced from the forehead down the nose. Four head position indicator (HPI) coils were fixed to the participant’s head and referenced to the other digitized landmarks. Two electrooculogram (EOG) electrodes were place above and below the left eye and near the outer canthi of each eye to record eye blink and saccade movements. Two electrodes were placed along the plane of the chest to collect the electrocardiographic (ECG) signal. MEG data were acquired with the participant seated upright in the scanner. Data were sampled at 2000 Hz. Head position and orientation relative to the MEG sensors were measured at the beginning of each run using the HPI coils. In addition to the magnetically shielded room, a MaxShield™ (Elekta Neuromag®) internal magnetic shielding system was employed to achieve maxshield compensation for additional noise reduction. In this system, compensation coils incorporated into the magnetically shielded room detect incoming noise signal and produce opposing signals of compensating voltages which cancel the effect of the incoming noise, thereby reducing background environmental magnetic fluctuations.

2.3.2. Signal Processing and Analysis

MEG. Pre-processing began with removal of external electromagnetic noise using the temporal signal-space separation (tSSS) method available in the Elekta Neuromag® MaxFilter™ software (Taulu & Simola, 2006). Subsequent pre-processing steps were completed in MNE-python (Gramfort et al., 2013; Gramfort et al., 2014). First, notch filters were applied to remove powerline interference at 60 Hz (width = 0.275), and at 55 Hz (width = 0.5) due to anomalous noise observed in the data from additional environmental electromagnetic activity. Biological artifact from ocular motion and QRS complexes identified via the horizontal and vertical EOG and ECG electrode channels was removed from the magnetometer and gradiometer channels through computation of independent components analysis (ICA) for those events per run. MEG sensors with signal strength greater than 5000 fT for magnetometers and 1000 fT/cm for gradiometers were manually marked and removed from the analysis prior to the generation of sensor waveforms. Additional data processing steps were computed using python (Python

Software Foundation. Python Language Reference, version 2.7. Available at http://www.python.org) and open-source scientific computing packages available in the SciPy library (Virtanen, et al., 2020; Oliphant, 2007; Millman & Aivazis, 2011) including NumPy (Oliphant, 2006; van der Walt, Colbert & Varoquaux, 2011), Ipython (Pérez & Granger, 2007), Matplotlib (Hunter, 2007), and pandas (McKinney, 2010). MEG data were Hilbert transformed to obtain the absolute amplitude and phase of the signal at a given time point. A digital lowpass butterworth filter (order 10) was subsequently applied at 30 Hz. The data were epoched into five 9-second segments within each block for a total of 30 segments per condition. The resulting segments were standardized within each of the 306 MEG channels in preparation for use of both magnetometer and gradiometer sensor data in the analyses. Each of the 9-second MEG data segments was cross-correlated with the time-locked corresponding attend passages, and ignore passages relevant for Cocktail Party 1- and 2-back conditions, across the full time scale of 9 seconds (18000 samples). Per participant, within each run, the five cross-correlated segments of 9 seconds were averaged per condition, and subsequently averaged across runs per condition for a given participant. The time window was further reduced to the initial 1000 ms phase-shift of the MEG response to the speech stimuli for focused analyses within this latency. Finally, the 306 MEG channels were averaged into 8 regions of interest (ROIs) corresponding to right and left temporal, frontal, parietal, and occipital lobes.

Speech Envelopes. Akin to the MEG data processing, speech stimuli were identically Hilbert transformed and lowpass filtered at 30 Hz (see Supplemental Figure 1). As there was subtle variability in length of speech passages presented, each approximately 50-second speech passage was cropped into 45-seconds to match the shortest attended passage and ensure all data included in analyses represent active online neural tracking rather than initial adjustments to the novel task blocks. Each resulting 45-second speech passage was parsed into five 9-second segments time-locked with the corresponding MEG data segments, as described above. Given the randomized presentation of speech stimuli and random pairs of attended and ignored passages per block per condition per participant, it is highly unlikely that the speech envelopes of the attended and ignored stimulus pairs were reliably correlated within a particular condition or at all.

MRI. Anatomical images of individual participants were processed using Freesurfer 5.1.0 software (http://surfer.nmr.mgh.harvard.edu; Dale, Fischl & Sereno, 1999; Fischl, Sereno & Dale, 1999). Through a series of automated algorithms, Freesurfer segments each voxel of the MRI images into white and gray matter and then estimates a triangular surface mesh at the gray and white matter boundaries to sub-millimeter accuracy (Fischl & Dale, 2000; Fischl et al., 2002). An additional mesh is calculated at the outside edge of the brain between the gray and pial tissues. Cortical thickness is calculated by the distance between the gray/white boundary and pial surface at any given point (Fischl & Dale, 2000). Individual participant cortical surface maps are subsequently registered to a spherical atlas based on cortical fold patterns, and the cerebral cortex of each participant is parcellated into anatomical regions using the structural information of brain gyral and sulcal folding (Desikan et al., 2006). Typically, the resulting individualized brain atlases would be subsequently used to back-project the MEG signal to localize to a presumed source, or specified brain region. While initial plans included analyses of the MEG signal by condition following atlas-based source localization, irreparable issues with registration of the MEG data to the digitized head shape for the majority of participants unfortunately rendered these aspirations very difficult given the resultant uncertainty of the anatomical registration. As such, MEG data were not ultimately co-registered to an anatomical brain atlas, and broad regions of interest (ROIs) were computed instead by averaging among MEG data channels contained within each cerebral lobe.

2.3.3. Statistical Analyses

Broadly, analyses were comprised of comparisons across conditions of both behavioral performance and of cross-correlation sequences of the MEG signal to the speech envelopes derived from the auditory stimuli. Statistical analyses were conducted using MATLAB (The MathWorks Inc., Natick, MA) and SPSS Statistics 24 (IBM Corp. Armonk, NY, USA).

2.3.3.1. Behavioral Performance

Behavioral performance will differ as a function of cognitive load. In order to test the hypothesis that higher average accuracy would be displayed in conditions with reduced cognitive load, two distinct analyses were conducted for accuracy of n-back responses and detections of “Alice” events. For n-back performance comparisons between conditions, accuracy was computed for each visual working memory condition within each auditory selective attention condition type. A repeated measures analysis of variance (rmANOVA) of accuracy employing a 3 auditory selective attention (PL, SS, CP) by 2 visual working memory load (1-back, 2-back) design was calculated to compare performance among conditions. Higher average accuracy was expected in both visual n-back and auditory “Alice” detections in the attend ear for conditions with reduced cognitive load (e.g., visual 1-back, auditory PL) relative to increased cognitive load (e.g., visual 2-back, auditory CP). Hence main effects of visual working memory load as well as auditory selective attention were hypothesized. An interaction was also expected to demonstrate that poorer performance in the Cocktail Party condition would be further reduced by the increased difficulty of the 2-back working memory load.

As the Passive Listening auditory selective attention condition does not require explicit detection of “Alice” events necessitating a response, only the Single Speaker and Cocktail Party auditory conditions were subjected to “Alice” hit accuracy analyses. Thus, a 2 auditory selective attention (SS, CP) by 2 visual working memory load (1-back, 2-back) rmANOVA was computed to test the hypothesis that higher cognitive load would result in reduced accuracy for “Alice” events. A main effect of auditory selective attentional load was expected such that “Alice” accuracy would be higher in the absence of competing auditory distraction of the Single Speaker condition compared to the Cocktail Party condition, which requires the filtering of auditory distraction. An interaction was also hypothesized to exhibit further reductions in accuracy for “Alice” events when the working memory burden was larger as in the Cocktail Party 2-back condition. Therefore, it was expected that the interaction would display the highest accuracy in the Single Speaker 1-back condition and the lowest accuracy in the Cocktail Party 2-back condition.

Performance in the visual working memory and auditory selective attention domains will be inversely related. The dual-task cost analyses examined the hypothesized trade off in attention allocation within a particular task domain at a given time, such that as performance increased in one task domain, performance in the concurrent dual-task would be consequently reduced. It was further expected that the performance cost would be more robust in the most cognitively demanding task (i.e., Cocktail Party 2-back). Thus, for each of the n-back conditions with explicit attended stimuli for detection of “Alice” events (Single Speaker, Cocktail Party), accuracy for the n-back task and “Alice” hits were computed for each block and averaged within condition for each participant. The resultant average n-back accuracy was correlated with the average accuracy for "Alice" events across all participants. Pearson correlation coefficients of performance in the simultaneous dual-tasks were obtained for each condition of interest: Single Speaker 1-back, Single Speaker 2-back, Cocktail Party 1-back, and Cocktail Party 2-back. Whereas the weakest inverse relationship was predicted in the Single Speaker 1-back task, the largest inverse correlation was expected in the Cocktail Party 2-back condition, as such a result would suggest that the performance cost is greatest in the most cognitively demanding condition. Using the Fisher r-to-z transformation (Fisher 1915; Fisher 1921), a z-score was calculated to assess the significance of the difference between the two correlation coefficients for each of the conditions compared. The 2-tailed significance thresholds obtained were subsequently evaluated for significance at a threshold of $p = .05$ after Bonferroni correction for multiple comparisons.

2.3.3.2. Neural Synchrony to Speech

Cross-correlation. Phase-locked neural responses to speech stimuli were computed with cross-correlation, a measure of the similarity of two time series at various lag positions (Figure 5). The resulting cross-correlation sequence is a set of correlation values of the signals across specified time lags. Within each of the 9-second epochs, cross-correlations were computed between the signal at each MEG sensor and the speech envelope of the attended passages within each auditory selective attention condition analyzed. Within the Cocktail Party condition, additional cross-correlations were computed between the signal at each MEG channel and the speech envelope of the ignored passages. All resulting cross-correlation sequences were averaged across the 9-second epochs by condition and for each participant. The subsequent averaged correlation sequences at each sensor was designated as contained within the left or right frontal, temporal, parietal or occipital lobe and further averaged within each designated region of interest (ROI). The averaged correlation sequence derived from each lobe by hemisphere ROI was binned by condition and plotted across time lags of 0.5 ms, up to a 1000 ms phase-shift, to determine phase-locking of the average neural signal to the speech envelopes of the attended passages, and of the ignored passages in the Cocktail Party condition.

Nonparametric cluster-based permutation test. A Monte Carlo, random sampling procedure was used to establish significance thresholds of cross-correlations that are corrected for multiple comparisons. Specifically, a nonparametric statistical test using cluster-based permutation (Maris & Oostenveld, 2007) was performed for each analysis detailed below. The specific conditions subject to random permutations are outlined separately for each statistical test described. Broadly the process entails the following (see Maris & Oostenveld, 2007 for further detail): Given that each participant has a participant-specific average for each experimental condition, the participant-specific averages of any two experimental conditions being compared were treated as a pair of observed data for that participant. The cluster-based permutation test consisted of randomly permuting the participant-specific averages for each condition pair in question within every participant (Maris & Oostenveld, 2007, pg. 188) essentially randomizing condition labels to the cross-correlation value sets of neural entrainment to the speech envelope. Cross-correlation values of each ROI were also subject to randomly assigned and permuted labeling among ROIs. Following 1000 permutations in order to attain a significance threshold for testing at the significance level of $p = .001$, the highest and lowest absolute correlation values across all lag positions for a given permutation were determined and a distribution of all the maximum and minimum correlation values was estimated. The upper and lower 5th percentile of the estimated null distribution were calculated to establish a 2-tailed significance threshold corrected for multiple comparisons across all lags and ROIs. Contiguous time samples above the computed test statistic threshold (*t* = 2.1) were selected and clustered into "adjacent time-samples that all exhibit a similar difference (in sign and magnitude)" (Maris & Oostenveld, 2007, pg. 180). The sum of the t-values within a given cluster will determine the cluster-level statistic, and the largest value is deemed the test statistic for evaluating the effect (Maris & Oostenveld, 2007, pg. 180). Distinct permutations and estimates of the null distribution to determine an appropriate significance threshold and cluster size, correcting for multiple comparisons, were conducted for each contrast analysis (detailed below). Each nonparametric statistical test with cluster-based permutation was computed using MATLAB.

2.3.3.2.1. Competing Noise Absent

In the absence of competing speech stimuli, phase-locking of the neural signal to the attended speech envelope will be greater in the condition with lower visual working memory load. Cross-correlations between the MEG signal and speech envelope of the attended passages were computed for the Single Speaker conditions by visual working memory load. The cross-correlation values of the Single Speaker 2-back condition were subtracted from those of the Single Speaker 1-back condition to obtain a difference score of the neural entrainment to the attended speech envelopes between visual working memory load conditions. For within-subjects comparisons, the cluster-based permutation test was conducted by randomizing the visual working memory condition labels (1-back, 2-back) of the participant-specific cross-correlation sequences within every participant and the nonparametric statistical test method described above was applied to establish a cluster size significance threshold corrected for multiple comparisons and across ROIs. Within each separate ROI, the size of contiguous t-value clusters comparing the visual working memory conditions at each lag position were analyzed for significance.

2.3.3.2.2. Competing Noise Present

In the presence of competing speech distraction, the difference in neural phase-locking to the speech envelope of the attended and ignored streams will vary by visual working memory load. In order to test the interaction hypothesis that the cross-correlation values of the neural entrainment to attended and ignored speech envelopes at a given lag position will be closer in value (i.e., less neural enhancement and suppression) in the 2-back Cocktail Party condition relative to the 1-back Cocktail Party condition, the cross-correlations between the MEG signal and speech envelope of the attended and ignored passages were computed separately for the Cocktail Party conditions by visual working memory load. For within-subjects comparisons, the interaction term of the cross-correlation value sets for passage type (attended or ignored) by visual working memory load (2-back [attend-ignore] – (1-back [attend-ignore]) were randomly permuted and subject to the nonparametric statistical test methodology described above to establish the significance threshold for comparison of adjacent time clusters at each ROI.

Furthermore, hypothesized planned comparisons were computed to provide potential evidence of greater enhancement to attended and greater suppression to ignored speech envelopes in the lower compared to higher visual working memory load condition. Firstly, within the Cocktail Party 1-back condition, higher cross-correlation of neural entrainment to the speech envelope of the attended passage was expected relative to the ignored passage. In order to obtain the null distribution for the cluster significance threshold of this analysis, the label assignment of the attended and ignored passage cross-correlations was randomized as the subject of the cluster-based permutation testing. Secondly, when assessing neural entrainment to the speech envelope of the attended passages only, lower cross-correlation values were expected in the Cocktail Party 2-back relative to the 1-back condition, suggesting greater enhancement to attended speech in the lower visual working memory load condition. Permutations randomizing the visual working memory load condition labels of only the cross-correlations to the attended passages were applied in the nonparametric statistical testing method to establish the cluster significance threshold. Finally, for examination of neural entrainment to the speech envelope of the ignored passages only, evidence of reduced suppression of the ignored passage in the more difficult visual working memory challenge was expected to be indicated by higher cross-correlation values in the Cocktail Party 1-back relative to 2-back condition. Permutations randomizing the visual working memory load condition labels of only the cross-correlations to the ignored passages were applied in the nonparametric statistical testing method to establish the cluster significance threshold.

3. Results

3.1 Behavioral Performance

Behavioral performance will differ as a function of cognitive load. A rmANOVA of n-back accuracy employing a 3 auditory selective attention (PL, SS, CP) by 2 visual working memory load (1-back, 2-back) design was computed to test the hypothesis that higher average accuracy would be displayed in conditions with reduced cognitive load. Main effects were found for both auditory selective attention, $F(2,40) = 17.63$, $p < .001$, $\eta_p^2 = .468$, and visual working memory load, $F(1,20) = 61.52$, $p < .001$, $\eta_p^2 = .755$. An interaction, $F(2,40) = 6.13$, $p = .005$, $\eta_p^2 = .235$, indicated reduced accuracy with increasing cognitive load (Figure 6). Specifically, within the auditory selective attention conditions, accuracy was significantly greater during the least cognitively demanding condition, Passive Listening (*M* = 91.9, *SE* = 1.3), relative to both the Single Speaker (*M* = 88.4, *SE* = 1.1), $p < .001$, and Cocktail Party (*M* = 86.4, *SE* = 1.2), $p < .001$, conditions, which were also significantly different from each other, $p = .022$. Additionally, as expected, the main effect of visual working memory load evidenced higher accuracy in the 1-back (*M* = 94.0, *SE* = 0.7) relative to the 2-back (*M* = 83.8, *SE* =1.6) condition, $p < .001$. Results supported the interaction hypothesis such that poorer accuracy in the Cocktail Party condition was further reduced by the increased difficulty of 2-back working memory load.

A second rmANOVA of correct detection of "Alice" events in the attended passages was computed in a 2 auditory selective attention (SS, CP) by 2 visual working memory load (1-back, 2-back) design. Note that the Passive Listening condition did not require detection of "Alice" events and thus was omitted from the present analysis. A main effect of visual working memory load was revealed, $F(1,18) = 6.137$, $p < .023$, $\eta_p^2 = .254$, with higher accuracy of attended "Alice" events in the 1-back condition (*M* = 83.4, *SE* = 2.8) relative to the 2-back condition (*M* = 79.5, *SE* = 3.0). There was no main effect of auditory selective attention, nor was an interaction found (Figure 7).

Performance in the visual working memory and auditory selective attention domains will be inversely related. Pearson correlation analyses assessing a dual-task performance cost were computed to test the hypothesis of a trade-off in attention allocation within a particular task domain at a given time. In addition to the notion that as performance increases in one domain, performance in the concurrent task domain will be consequently reduced, it was further expected that the performance cost would be strongest in the most cognitively demanding task (Cocktail Party 2-back). Comparisons of Pearson correlations between n-back and "Alice" hit accuracy by condition revealed no differences in performance cost among dual-task conditions (all $p > .05$ after Bonferroni correction for multiple comparisons; see Figure 8). Furthermore and counter to expectation, only the Single Speaker 1-back condition demonstrated a moderate correlation of dual-task performance, $r = 0.45$, indicating that higher performance in one dual task was related to higher performance in the concurrent task. While the Single Speaker 2-back condition demonstrated a similar dual-task performance relationship albeit to a lesser extent ($r = 0.20$), dual-task performance in both the Cocktail Party 1-back ($r = -0.12$) and 2-back ($r = 0.04$) conditions appeared largely uncorrelated.

3.2 Neural Synchrony to Speech

3.2.1 Competing Noise Absent

In the absence of competing speech stimuli, phase-locking of the neural signal to the attended speech envelope will be greater in the condition with lower visual working memory load. Comparison of the Single Speaker 1- and 2-back conditions revealed a significant time cluster of cross-correlation values in the left temporal ROI from a latency across 368.5 – 414 ms ($t \geq 2.1$, $p \leq .001$) in the condition with lower working memory load, Single Speaker 1-back (Figure 9). No additional time clusters of adjacent lag points were significant, nor did other ROIs demonstrate significant cross-correlation time clusters.

3.2.2 Competing Noise Present

In the presence of competing speech distraction, the difference in neural phase-locking to the speech envelope of the attended and ignored streams will vary by visual working memory load. The interaction examining the cross-correlation values of the neural entrainment to attended and ignored speech envelopes by visual working memory load revealed no significant adjacent time clusters of the cross-correlation sequences for any of the 8 ROIs tested. Planned comparisons within the Cocktail Party condition were subsequently calculated to examine specific hypotheses regarding potential evidence for greater enhancement to the attended speech envelope and greater suppression to the ignored speech envelope under lower compared to higher visual working memory load. Upon assessing neural entrainment to the speech envelope of the attended passages only, lower cross-correlation values were expected in the Cocktail Party 2-back relative to the 1-back condition to suggest greater enhancement to attended speech under lower visual working memory load. Results indicated a significant time cluster of cross-correlation values in the right frontal ROI from a latency of 362.5 – 460.5 ms ($t \geq 2.1$, $p \leq .001$; Figure 10) for the 1-back condition. Within the Cocktail Party 1-back condition, higher cross-correlation indexing stronger neural entrainment to the speech envelope of the attended passage was expected relative to the ignored passage. Contrary to prediction, results demonstrated a significant time cluster of cross-correlation values in the left temporal ROI from a latency of 15.5 – 97.5 ms ($t \leq -2.1$, $p \leq .001$) to the ignored relative to the attended speech passage (Figure 11). Finally, neural entrainment to the speech envelope of the ignored passages were examined to uncover potential evidence of reduced suppression of the ignored passage in the more difficult visual working memory challenge. Thus, higher cross-correlation values to index active tracking for suppression were expected in the 1-back relative to 2-back condition. Results demonstrated a significant time cluster of cross-correlation values in the left parietal ROI within a brief latency from 0.5 – 76.5 ms ($t \geq 2.1$, $p \leq .001$) in the 1-back condition (Figure 12).

4. Discussion

The present study broadly investigated the impact of multitasking on selective attention to speech with the general hypothesis that increased task load would impair selective attention to the attended speech stream both in the presence and absence of competing distraction. As expected, behavioral results indicated that increases in visual working memory load were associated with performance decreases in both visual and auditory dual-task modalities. However, auditory distraction did not impact accurate detection of the target speech. Contrary to expectation, dual-task cost was not significantly different among multitask conditions. Together, these results suggest that competing task load across modality, rather than simply irrelevant distraction within modality, may occupy substantial neural resources to perform a concurrent task, resulting in reduced overall multitask performance.

Broad investigation of neural phase-locking to attended and ignored speech under varied simultaneous working memory load revealed significant adjacent time clusters in the left temporal, left parietal, and right frontal lobes. When competing noise was absent, lower simultaneous visual working memory load was associated with greater neural entrainment within left temporal structures to the attended speech envelope. However, in the presence of competing distraction in which auditory selective attention demands are greater, right frontal structures reliably entrained more strongly to the attended speech envelope under lower simultaneous visual working memory demand. Yet when visual working memory load was held constant in the presence of competing speech, phase-locking of neural firing in the left temporal lobe was greater to the ignored relative to the attended speech passage, though at a shorter latency. Finally, when comparing neural oscillations to ignored speech passages, lower simultaneous visual working memory load was associated with greater neural synchrony within left parietal structures on a similarly shorter time scale. No specific interaction of neural entrainment to attended or ignored speech passages by visual working memory load was found.

4.1 Behavioral Performance

Behavioral performance results broadly supported the general hypothesis that increased task demand would impair multitask performance. Results further supported the specific hypothesis that visual working memory performance incrementally declined with increasing levels of task demand in both auditory and visual dual-task domains. More specifically, results also provided evidence for the hypothesis that poorer n-back accuracy in the Cocktail Party condition was further reduced by the increased demand of the 2-back working memory load. Not surprisingly, these findings strongly resemble those of the extant working memory load literature employing visual and auditory n-back paradigms in the face of both unimodal and cross-modal distraction (Pesonen et al., 2007; de Fockert et al., 2001; Lavie & de Fockert, 2005; Lavie et al., 2004; Konstantinou et al., 2014; Lavie 2005; Weissman, Warner, & Woldorff, 2004). Less well-studied to date is how the load relationship to performance is impacted in a dual-task challenge with simultaneous auditory and visual task goals of varying load. In the present novel study, the level of cognitive demand was manipulated in both the visual and auditory domains of the dual-task paradigm. While greater visual working memory load yielded performance reductions in both the visual and auditory modalities, the level of auditory distraction alone did not appear to impact accurate detection of the target speech (i.e., “Alice” events). Brand-D’Abrescia and Lavie (2008) noted similar findings that within-modality distraction only impacted performance when the concurrent working memory demand was greater.

Additionally, dual-task cost was not significantly different across multitask conditions. In fact, a moderate positive correlation was found in the condition with the lowest cognitive demands for both visual working memory (1-back) and auditory selective attention (Single Speaker). Maintaining the lack of auditory distraction (Single Speaker) while increasing visual working memory load (2-back) also yielded a similar relationship though to a smaller degree. For the conditions with competing auditory distraction (Cocktail Party), no dual-task performance relationships were evident regardless of visual working memory load. When unpacking these results, it is important to consider that the moderate dual-task correlation in the Single Speaker 1-back condition revealed that participants who were more accurate in target detection in one task domain were similarly more accurate in the concurrent task domain. Of note, accuracy was generally quite high for both of the dual tasks in the Single Speaker 1-back condition overall. The same was true for the Single Speaker 2-back, though greater variability of performance accuracy was observed in both the visual working memory and auditory selective attention dual tasks. Therefore, participants who performed well under low task demand performed consistently well in both dual task modalities when competing noise was absent.

Interestingly, in the presence of competing noise, no discernible relationship in dual-task cost was observed regardless of visual working memory load. Yet significant declines from the 1-back to 2-back Cocktail Party condition were indicated for both n-back and “Alice” accuracy. There are several factors that may account for this unexpected finding. First, the introduction of competing speech sounds may have rendered the total task demand substantially high at the individual trial level, which may not be adequately captured in participant level averages across runs. As such, potential momentary dual-task tradeoffs may be masked by the averages and hence lack meaningful trial-specific data in the analyses. As previously reported, shifts in attention allocation necessary for optimal multitasking must occur very rapidly at the trial level to successfully manage task goals (Monsell, 2003; Cole et al., 2013; Cole, Laurent, & Stocco, 2013; Dosenbach et al., 2006; Niendam et al., 2012; Cai et al., 2015; Seeley et al., 2007). Additionally, the dual-task correlation in the Single Speaker 1-back condition may simply represent individual differences in participants' abilities to perform target detection tasks. Given the lower demand of the Single Speaker 1-back condition, the moderate correlation may simply reflect baseline ability to perform a simple dual-task. Under such a premise, these results do not specifically highlight a dual-task cost (or benefit in this case), but rather underscore baseline variability in dual-task performance among participants. Of note, the correlation declined, although not significantly, with increased visual working memory demand and as participant responses became more variable.

Another limitation in the dual-task cost analyses is the fact that only accuracy for "Alice" hits in the attended passage was investigated, whereas discriminability between attended and ignored "Alice" events was not analyzed. In particular, false alarm rates (i.e., responses to "Alice" in the ignore ear) were not a factor in the present analyses. As such, it cannot be determined whether increases in cognitive demand may result in greater difficulty discriminating between "Alice" events in the attended versus ignored passage. The present analyses did not explicitly test whether participants indiscriminably responded to "Alice" events regardless of the target passage. Notably, the questions of detectability and discriminability are different and may be distinctly impacted by simultaneous cognitive load in a multitask situation. Further, the neural processes underlying detectability of "Alice" in the attend ear and discriminability of "Alice" in attended and ignored passages may be differentially affected by concurrent cognitive demand under multitask constraints. Utilization of a sensitivity index such as *d'* may help to better parse differences in performance related to discriminability when competing distractor speech is present. Computation of *d'* in the present study was challenging and unreliable as there were multiple instances in which an “Alice” event in the attended and ignored ear somewhat overlapped within the allowable response window of up to 2500 ms post-stimulus onset. Due to programming software limitations for recording several responses in overlapping time windows from multiple continuous stimuli presented over a 50 second span, we were unable to reliably distinguish the intended stimulus for a given auditory response recorded. Importantly, this was not the case for the visual working memory responses as each stimulus could be programmed as a distinct event with responses required per stimulus. Therefore, for the purposes of the present study, only “Alice” events in the attended passages were analyzed. Of note, presentation of all speech stimuli and attend/ignore stimulus pairs were randomized. Thus, there is minimal concern for a systematic issue regarding double presentations of “Alice” from both attended and ignored passages in close temporal proximity within a given condition. Ultimately, any button responses recorded for “Alice” events were attributed to the corresponding “Alice” in the attended passage if occurring within the allowable time window for correct responses (200-2000 ms post-stimulus onset). While acknowledging that current analyses do not eliminate the potential for responses to incidental “Alice” events in the ignored passage, since reliable attribution of the button response to an attended or ignored “Alice” in these instances was not possible, the attended “Alice” events were given priority for the purposes of the analyses presented here.

Participants also demonstrated substantially larger inter-individual variability in “Alice” hit accuracy indexing auditory selective attention performance (group standard deviations of performance range from 12-14% accuracy), relative to the generally high and less variable visual working memory accuracy (group standard deviations of performance range from 2-9%

accuracy). Yet, as expected, greater variability in the 2-back conditions was evident regardless of the simultaneous auditory selective attention condition. It is also plausible that the differential rate at which targets occurred in each of the dual-tasks reduced the level of direct performance comparison able to be made in the dual-task cost analyses. For a given block, 16-18 separate responses were required in the n-back tasks, while only 4-6 “Alice” events comprised the auditory selective attention task blocks. Beyond the difference in total trials and hit rates of the dual-tasks, the type of attention allocation required for efficient execution of each of the simultaneous dual tasks was also likely non-equivalent. Finally, it is unlikely that participants were equally or consistently prioritizing one dual-task over the other for the full block duration, as rapid shifting at the individual trial level was likely to be more effective.

4.2 Neural Synchrony to Speech

Behavioral results suggesting that competing task load across modality may occupy substantial neural resources were further supported by the neural entrainment results. The general hypotheses regarding neural entrainment to speech posited that phase-locking of the neural signal to the attended speech streams would be stronger under reduced working memory load in both the presence and absence of competing speech. When competing noise was absent, lower concurrent visual working memory load was associated with greater neural entrainment within the left temporal lobe to the attended speech envelope. The significant time cluster of entrainment was observed from a latency of 368.5 – 414 ms, a time course corresponding to delta and theta changes reflecting the syllabic, phrasal, and sentence level distinctions characteristically tracked via the speech envelope (Abrams, Zecker & Kraus, 2008; Abrams, Zecker & Kraus, 2009; Kubanek et al., 2013; Aiken & Picton, 2008; Lou & Poeppel, 2007; Ding, Chatterjee & Simon, 2014; Ding & Simon, 2012a; Ding & Simon, 2012b; Keital et al., 2016; Ding et al., 2016). Results replicate findings from prior work demonstrating neural synchrony to the speech envelope as a primary factor for speech comprehension in the absence of noise (Bidelman, 2016; Moon & Hong, 2014; Ding, Chatterjee, & Simon, 2014; Rimmele et al., 2015). Current findings in the left temporal ROI are strongly in line with expectations of neural involvement from auditory perceptual and higher-order language integration regions when tracking the speech envelope (Keitel et al., 2017; Abrams, Zecker & Kraus, 2008; Abrams, Zecker & Kraus, 2009; Kubanek et al., 2013; Aiken & Picton, 2008; Lou & Poeppel, 2007). Additionally, the latency observed peaking around 400 ms in the left temporal lobe notably corresponds to the time scale of semantic processing of speech stimuli (Vartiainen et al., 2009; Lau et al., 2013), especially in the left middle temporal gyrus (Lau, Phillips, and Poeppel, 2008). Further, recent work has demonstrated the particular role of posterior middle temporal gyrus at a similar latency in listening situations where ongoing retrieval and updating of information is necessary to form judgments of thematic content (Teige et al., 2019). Continual formation of such thematic judgments is likely required to optimize comprehension while tracking the convoluted speech passages from *Alice in Wonderland* and *Through the Looking Glass* utilized in the present study.

Results further support hypotheses of higher neural entrainment under lower cognitive demand, when ample top-down neural resources are presumably available to command perceptual cortices to enhance representation of the relevant information (Mesgarani and Chang, 2012; Zion Golumbic et al., 2013; Zion Golumbic et al., 2012; Ding, Chatterjee & Simon, 2014). Yet, when cognitive demand is increased to the 2-back visual working memory load, top-down resources available are likely reduced and neural entrainment is less robust as a consequence.

Under greater working memory constraints, top-down control regions are further occupied with the cognitive burden of increased monitoring and updating of the visual targets to appropriately execute the behaviorally relevant goals of the 2-back load. As such, results support the hypothesis that top-down mechanisms may not be able to allocate sufficient neural resources to optimally track the attended speech to the same extent while otherwise engaged in a more demanding concurrent task.

Interestingly, in the presence of competing distraction when auditory selective attention demands are greater, right frontal structures reliably entrained more strongly to the attended speech envelope under lower visual working memory demand. The time course of the significant cluster was 362.5 – 460.5 ms, similarly corresponding to neural tracking in the delta and theta modulation range of the speech envelope. While previous studies have primarily demonstrated neural entrainment of auditory cortex to the speech envelope, a smaller number of studies have also reported neural entrainment beyond auditory cortex. Right frontal entrainment to delta rhythms in particular (Gross et al., 2013; Giordano et al., 2017) has been linked to the role of right fronto-temporal structures in processing prosody of speech (Bourguignon et al., 2013; Friederici 2011). Moreover, greater involvement of frontal regions under lower working memory load (e.g., when cognitive control resources are less burdened) is corroborated by extensive report in the literature implicating the frontal lobes in a vast array of cognitive control processes (Corbetta & Shulman, 2002; Corbetta et al., 2008; Dosenbach et al., 2007; Vincent et al., 2008; Power et al., 2011; Power & Petersen, 2013; Geerligs et al., 2014; Ptak, 2012; Sadaghiani & D'Esposito, 2015; Menon, 2015), including managing streams of competing concurrent information (Monsell, 2003) when highly adaptive cognitive control is necessary (Cole et al., 2013; Cole, Laurent, & Stocco, 2013; Dosenbach et al., 2006; Niendam et al., 2012; Cai et al., 2015; Seeley et al., 2007). In addition to monitoring dual-task set and rapidly shifting between dual tasks, which impose significant demand on the limited resources of the cognitive control network (Merian, Kessler & Adi-Japha, 2008), selectively attending to speech likely further increases the neural encumbrance. Results showing higher contiguous cross-correlations in frontal regions to the attended speech under lower visual working memory load underscore the importance of frontal cortex in effectively managing concurrent streams of information in a multitask scenario (Rushworth et al., 2002). Enhanced involvement of frontal structures is further consistent with prior report of medial frontal/cingulate regions activated during brief intervals while switching from one task to another (Rushworth et al., 2002). Moreover, pertinent dissociable functions of anterior cingulate cortex have been reported such that dorsal anterior cingulate aids in focusing attention on the relevant stimulus, whereas rostral anterior cingulate detects conflict from the irrelevant stimulus in a cross-modal paradigm (Weissman, Warner, & Woldorff, 2004). Likewise, present findings of neural entrainment in the right frontal lobe amid competing noise may alternatively correspond to the role of right frontal gyrus in cognitive inhibition across different response modalities (Chikazoe et al., 2007). Successful execution of response inhibition (Swick, Ashley, and Turken, 2008; Chikazoe et al., 2007) and response bias adjustment during decision-making (Reckless et al., 2014) is paramount for effective multitasking in the face of irrelevant distraction. Such findings of frontal involvement are also consistent with prior research demonstrating top-down modulation of auditory perceptual cortex by task load both for discrete speech syllables (Sabri et al., 2014; Sabri et al., 2013) as well as for selective processing of speech streams (Keitel et al., 2017).

A secondary aim of the present study sought evidence for neural suppression of the ignored speech signal, which was hypothesized to be less well managed under higher cognitive demand. Holding visual working memory load constant, stronger neural entrainment to the attend speech envelope was expected relative to the ignored passage. However, contrary to prediction, phase-locking of neural firing in the left temporal lobe was unexpectedly greater to the ignored speech envelope relative to the attended envelope at a latency of 15.5 – 97.5 ms. Although an unanticipated finding, it is encouraging to uncover left temporal tracking of ignored speech, as prior work has suggested that active tracking by auditory cortex of unattended or distractor passages may also be necessary for an effective suppression mechanism (Horton et al., 2013; Makov and Zion Golumbic, 2020). The short latency of the significant time cluster is initially perplexing; however, it is important to reiterate that neural tracking of the speech envelope is most profitable in the absence of competing noise, and tracking of the temporal fine structure must be brought online for adequate separation and intelligibility of the target speech in the presence of competing distraction (Bidelman, 2016; Moon & Hong, 2014; Ding, Chatterjee, & Simon, 2014; Rimmele et al., 2015). The current neural entrainment analyses were conducted after the raw speech signal was reduced to mainly the delta and theta oscillations of the speech envelope. As such, potential contribution from the temporal fine structure is lost, though such information may be most critical for effective separation of speech streams necessary for selective attention to the target speech. However, all is not lost on the temporal envelope analyses for evidence of potential suppression. As characterized by the selective entrainment hypothesis (Zion Golumbic et al, 2013), entrainment to the delta and theta oscillations of the temporal envelope increases the baseline for excitatory firing to improve perception of information contained within the temporal fine structure, ultimately enhancing the signal to the attended speech stream. Teng et al. (2017) demonstrated that neural theta oscillations also track speech modulations in the gamma, beta, and alpha frequency bands. While enhancement of the attended speech stream was not demonstrated in the present results, evidence of tracking the ignored speech at latencies akin to the temporal fine structure changes may provide evidence for active tracking to suppress distractor speech.

Additionally, as cognitive load becomes considerably burdened, effectively ignoring interfering information poses a greater challenge due to immense taxing of neural resources (Konstantinou et al., 2014). Moreover, how difficult a stimulus is to ignore also modulates the response to distraction (Bidet-Caulet et al. 2007; Chait et al. 2010; Noonan et al. 2018; Melara et al. 2002, 2012). In fact, recent work has shown that rhythmic auditory distraction was less interfering than random non-rhythmic distraction (Devergie et al., 2010, Rimmele et al., 2012), and during a difficult task (Andreou et al., 2011). In some cases, the rhythmic irrelevant stimuli actually facilitated responses to the relevant stimuli in a manner that corresponded to the rhythm of the irrelevant distraction (Escoffier et al., 2010). As such, it is also possible that instances of overlap in "Alice" events in the attended and ignored passages may have facilitated "Alice" detectability in the attend ear, particularly if the ignore "Alice" shortly preceded the attend "Alice" (see Makov and Zion Golumbic, 2020). Comparisons of rhythmic and non-rhythmic distraction during a dichotic listening auditory selective attention paradigm revealed varying time scales of event related fields (ERF) observed in ipsilateral and contralateral hemispheres to the distractor sounds (Makov and Zion Golumbic, 2020). The ERF differences in ipsilateral hemisphere were demonstrated closely in time to the distractor onset between 0 – 40 ms, as well as at a later latency of 80 – 120 ms (Makov and Zion Golumbic, 2020). Notably, these observed ERFs were localized among a distribution of inferior frontal, superior temporal, and parietal regions. Importantly, findings suggest that not only are top-down predictions crucial for modulating sensory and integrative speech processing sites, but that top-down prediction gleaned from temporal aspects of the task-irrelevant sounds may also facilitate improved behavioral execution of relevant task goals (Sussman 2017; Makov and Zion Golumbic, 2020). Such findings bolster the growing scientific evidence for a neural mechanism employing top-down modulation of tracking interfering speech to effectively suppress cortical representations of the task-irrelevant information (Horton, D'Zmura & Srinivasan, 2013; Kong, Mullangi & Ding, 2014; Kong, Somarowthu & Ding, 2015; Makov and Zion Golumbic, 2020; Barbas et al., 2013; Salo et al., 2017; Kuchibhotla and Bathellier, 2018). Thus, the present results may be capturing aspects of a suppression mechanism operating efficiently under lower working memory load.

Effective maintenance and tracking of the distractor speech on an earlier time scale may be most efficient for suppression of the irrelevant, and therefore facilitate attention to the target speech. Ignoring the distractor speech stream likely requires a mechanism to shut down the auditory noise in a rather continuous fashion. As such, an early suppression process may be ideal to deactivate phonemic decoding of the ignored stream in order to optimally concentrate on the behaviorally relevant attend passage and visual working memory stream. Deactivation of typical linguistic processing may impose a greater challenge on the cognitive control network than managing the visual working memory load or enhancing representation of the attended speech. Thus, such an efficient presumed mechanism likely requires very early deactivation to be optimally effective in suppression. For example, Nora et al. (2020) demonstrated that in the absence of competing noise, non-linguistic environmental sounds were decoded within 50 ms while phonemic decoding of linguistic sounds occurred around 100 ms. Hence, in the presence of competing noise, the earlier latency may represent an effective time course to accurately deactivate phonemic processing of the ignored passage before the irrelevant sounds become processed as linguistic content.

Finally, when varying visual working memory load and comparing neural oscillations to ignored speech passages, lower simultaneous visual working memory load was associated with greater neural synchrony within left parietal structures at a latency of 0.5 – 76.5 ms. As predicted, higher phase-locking for active tracking to effectively suppress the ignored speech stream was demonstrated in the less cognitively demanding 1-back relative to 2-back Cocktail Party condition. As discussed above, the shorter latency of the significant adjacent time cluster observed may also relate to the need to process the temporal fine structure to segregate the target speech among the noise, coupled with the recent evidence that theta oscillations in the brain also track speech information discerned from modulations in the gamma, beta, and alpha bands. The left parietal entrainment to the ignored speech may work in concert with the early left temporal suppression effect proposed above. Coordinated rapid entrainment within left parietal structures may reflect a potential necessity for tracking aspects of semantic representation for prompt meaning construction that unexpectedly becomes behaviorally relevant. Active monitoring of unattended or ignored information thus allows for the listener to instantaneously shift attention should information contained within the competing speech become suddenly relevant. Thus, left parietal entrainment to the ignored speech at rapid latencies may serve to both ensure effective suppression and potentially alert frontal regions to enhance the distractor stream in the event that ignored information becomes behaviorally relevant. For instance, it is possible that “Alice” events were more heavily tracked than other spoken words in the ignored speech, as their meaning was potentially behaviorally relevant. The added level of effective response inhibition once the “Alice” event is designated to the “ignore ear” likely occurs at a later latency around 100 ms (Boehler et al., 2009). The timescale of the left parietal ROI could also reflect the high temporal resolution necessary for speech intelligibility and decoding to subsequently make momentary decisions about how to respond behaviorally. Even though the speech stimuli were explicitly chosen due to the convoluted nature of the passages, the target word "Alice" remained constant. A consistent speech target word throughout the task duration was chosen to reduce the already high working memory demand of the dual tasks; mitigate the reliance on adequate one-trial learning (i.e., from instructions with an ever-changing target word per speech passage); and to lessen further multitasking, ultimately creating greater cognitive burden throughout the task.

4.3 Limitations and Future Directions

It is important to acknowledge additional limitations to those outlined above to ensure future work might expand upon the present findings. Regarding the neural entrainment analyses, collapsing the MEG data by averaging channels into large ROIs substantially reduces the resolution to localize entrainment to specific brain regions. Use of source localization to a parcellated brain atlas would aid in clarifying the roles of various regions implicated in the neural entrainment analyses. While the present results found significant entrainment in relevant regions of interest, more robust interpretation of results might be garnered from source localization in future work. Additionally, the current study exclusively focused on analyses of the temporal envelope of the speech stimuli. Yet, inclusion of higher speech frequencies to index aspects of the temporal fine structure may prove useful for characterizing the mechanisms by which the brain tracks and reconciles competing speech streams. Analyses employing the temporal fine structure may further elucidate critical operations of a proposed suppression mechanism. While the temporal envelope remains essential to the selective attention to speech process, the temporal fine structure is important for speech intelligibility and parsing speech streams in a multi-talker scenario.

Turning to the behavioral analyses, reaction time differences among the various conditions were not assessed in the current study. As reaction times tend to demonstrate longer latencies and greater variability under higher cognitive demand (Balasubramaniam et al., 2015), reaction time analyses could illuminate relationships among conditions that may be masked by use of broad condition accuracy. Additionally, the present investigation did not include a selective attention control condition wherein participants passively viewed the n-back shapes in a 1- and 2-back fashion and simply engaged in the auditory selective attention tasks (e.g., responded to "Alice" events in the attend passage without the added load of engaging in the visual working memory task). Analogous to the Passive Listening condition for visual working memory with passive auditory distraction, a "Passive Viewing" condition may have been a useful control for measuring baseline auditory selective attention with passive visual distraction. As such, the present investigation is unable to equivalently characterize and compare single tasks with cross-modal passive distraction as a lower level of cognitive demand in both dual-task domains.

Given the inter-individual variability in behavioral performance in the current study, future studies may wish to examine whether individual performance corresponds to other measures of executive functioning (e.g., switching, inhibition, monitoring, updating). Furthermore, relating the degree of intra-individual variability on "Alice" responses to various measures of executive functioning may also aid in uncovering essential processes for consistent and efficient dual tasking. Such data would provide sufficient information to investigate a linking hypothesis that greater intra-individual variability is associated with larger dual-task cost due to differential ability to effectively manage multiple sources of information. Finally, it is important to note that many factors not explicitly measured in the present study can substantially impact attention allocation, including motivation, effort, arousal, and vigilance (Strauss and Francis, 2017). Such factors as they relate to performance and neural entrainment may be considered in future work.

4.4. Broader Implications

The present study was conducted in the context of healthy young individuals, as a foundation to establish how the brain deploys cognitive control when multitasking, particularly as tasks become increasingly difficult to manage and neural resources are likely overloaded. Greater understanding of how the healthy brain attempts to tackle the multitask process could have significant implications for understanding the aging brain as well as disorders of attention and executive functioning. Efficient cognitive control (e.g., multitasking, selective attention, working memory, set-shifting) often declines in the normal aging process, in aging pathologies such as mild cognitive impairment and various dementias, as well as in developmental disorders involving attention and executive control processes (e.g., Attention Deficit/Hyperactivity Disorder (ADHD)). Furthermore, chronically experiencing these cognitive challenges is associated with negative psychosocial outcomes (e.g., depression, anxiety), which can in turn impact cognition and daily functioning (Cambridge et al., 2018; Ajilchi & Nejati, 2017).

The present findings substantiate a foundation for investigating impairments in cognitive control and selective attention to speech associated with normal aging and neurological pathology. Extensive research demonstrates that selective attention and working memory functions that support speech processing in noise tend to decline with advancing age (Gazzaley & D’Esposito, 2007; Glisky 2007; Healey, Campbell, & Hasher, 2008). Although the ability to process task-relevant information remains largely intact in normal aging, the ability to suppress task-irrelevant information declines with age (Geerligs et al., 2014; Helfer, Mason and Marino, 2013; Rajan and Cainer, 2008; Wong et al., 2009). Notably, even adults with normal hearing thresholds exhibit difficulty with efficient separation and processing of the target speech stream amid competing noise relative to their younger counterparts. Among adults with normal hearing thresholds, Parthasarathy et al. (2020) found that speech intelligibility thresholds in a multi-talker scenario varied greatly, yet neural phase-locking to frequency modulation cues predicted speech intelligibility. In addition, impaired hearing in the context of normal aging is associated with greater difficulties in selective attention, working memory, and cognitive switching (Shinn-Cunningham and Best, 2008). Moreover, neurocognitive disorders observed in pathological aging also involve disrupted cognitive control well beyond that of normal cognitive aging, and are reported across a multitude of etiologies including cerebrovascular (Sudo et al., 2017) and neurodegenerative conditions such as Parkinson's Disease (Bezdicek et al., 2018), frontotemporal dementia (Moheb et al., 2017) and Alzheimer's Disease (Melrose et al., 2018; Guarino et al., 2018; Levinoff et al., 2004).

Research across healthy aging (Geerligs et al., 2014), neurodegenerative disorders (Drzezga et al., 2005), ADHD (Aboitiz et al., 2014), depression (Desseilles et al., 2009), and anxiety (Stout, Shackman, & Larson, 2013) similarly report reduced ability to suppress and filter out competing irrelevant distraction, as well as unwanted, negative, or threat-related information in particular among individuals with anxiety and depression. Further, internal thoughts, especially in the context of anxiety and depression, can be very distracting to the task-at-hand. Thus, further characterization of the suppression mechanism is of paramount clinical utility, as aberrant suppression of the irrelevant may have implications for interventions across various clinical contexts. Interventions such as cognitive training have proven useful in healthy aging

(Mozolic et al., 2011). Pharmacological and other behavioral interventions that focus on bolstering suppression mechanisms may promote greater fluidity of attention allocation with less effortful shifts from one task to another. For instance, mindfulness practices may help to train the brain to strengthen both the enhancement and suppression mechanisms and ultimately lead to better command of cognitive control systems (Moore & Malinowski, 2009). Thus, understanding the suppression mechanism of the irrelevant distraction in-the-moment may be a key basis for finding ways to target and train the brain to improve selective attention and enhance overall active engagement in daily life.

4.5 Conclusions

The present study sought to investigate the impact of multitasking on selective attention to speech in healthy young individuals. As predicted, behavioral findings demonstrated that increased task load reduced selective attention to speech in both the presence and absence of competing distraction. Notably, auditory distraction alone did not hamper detection of the target speech, and no specific dual-task performance costs were found among multitask conditions. Nevertheless, visual working memory results suggested that competing task load across modality occupies substantial neural resources. The neural entrainment findings illuminated the impact of cognitive demands on neural enhancement and suppression of task-relevant and -irrelevant information, respectively. Stronger entrainment to attended speech under low working memory load involved left temporal regions with no auditory distraction and right frontal structures when selectively attending amid competing speech. At these lower levels of cognitive demand, entrainment to the attended speech occurred in a time course corresponding to the speech envelope. Conversely, neural entrainment to the ignored speech occurred at shorter latencies in the left temporal lobe when compared to the attended speech, and in left parietal regions under lower working memory demands. Taken together, the present findings provide evidence for both top-down enhancement and suppression mechanisms in the service of selective attention to speech while multitasking. In accordance with previous work, persistent enhancement may occur at the lower frequencies of the speech envelope to optimize neural firing for cortical enhancement at critical points for speech comprehension. Yet, effective suppression of the distractor speech may require earlier tracking for either swift deactivation of the ignored stream, or active monitoring to potentially shift attention should previously ignored information become behaviorally relevant. The present findings further demonstrate that both mechanisms for neural enhancement and suppression were modulated by concurrent task load.

5. References

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APPENDIX

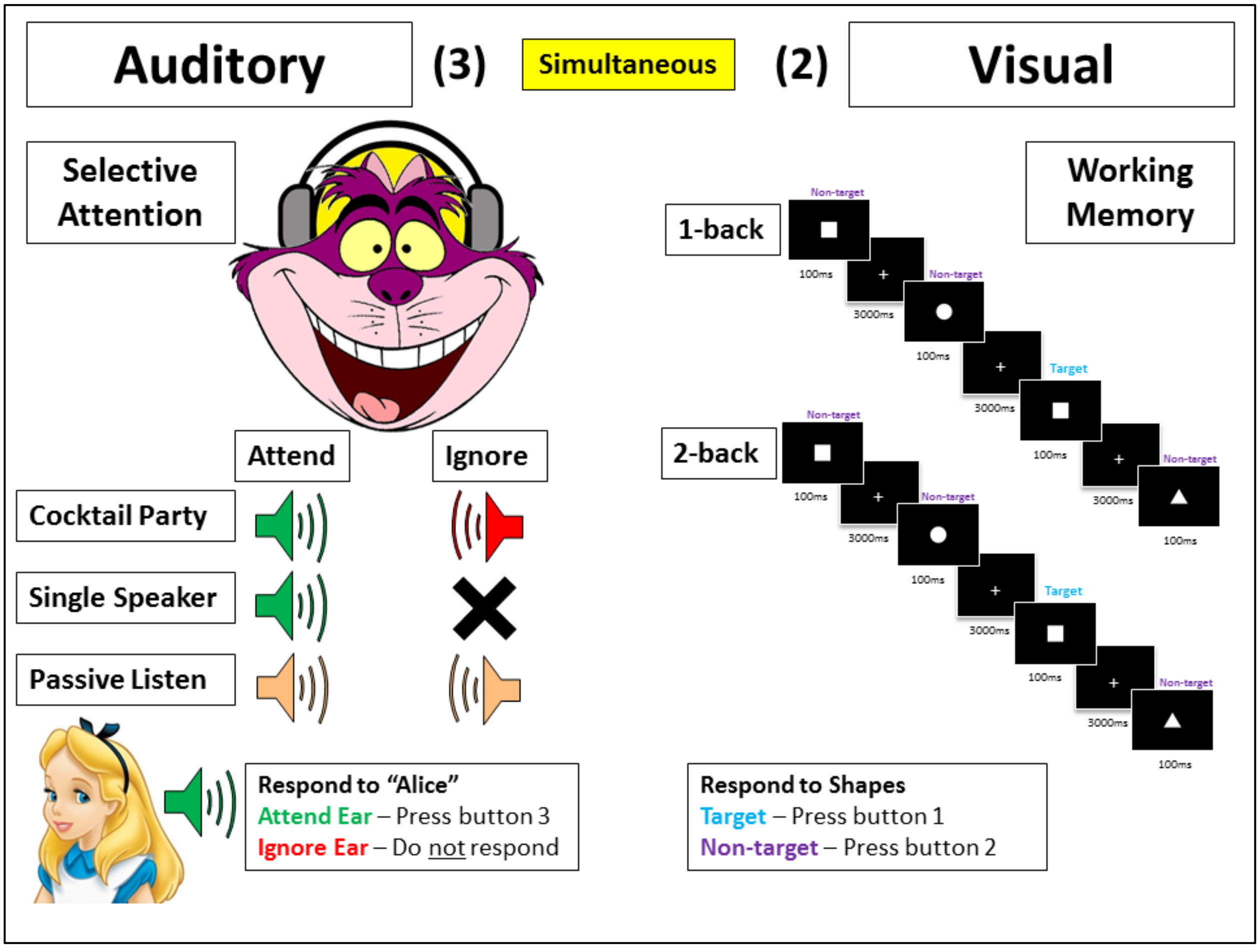


Figure 1. Dual-task paradigm schematic. In a 3 (auditory selective attention) by 2 (visual working memory) design, participants simultaneously engaged in both auditory and visual tasks. Each auditory condition presented concurrent attend and ignore passages dichotically with varying response instructions in the following 3 conditions: Cocktail Party (attend to passage in specified ear and make button response each time the word "Alice" is heard in the attend ear; ignore passage presented in opposite ear and do not respond to the word "Alice" in the ignore passage); Single Speaker (attend to passage in specified ear and make button response each time the word "Alice" is heard in the attend ear; no concurrent sound presented in opposite ear, thus no auditory stimuli to ignore); Passive Listen (distinct passages presented dichotically with explicit instruction to passively listen and no need to respond to any auditory events; intended to match acoustic energy of Cocktail Party condition while removing the explicit need for auditory selective attentional load). The 2 visual working memory tasks consist of a 1-back and 2-back task in which participants are instructed to make a button response classifying each shape presented as either a "target" or "non-target" according to the current n-back rule. Each auditory selective attention condition was paired with each visual working memory condition for a total of 6 conditions.

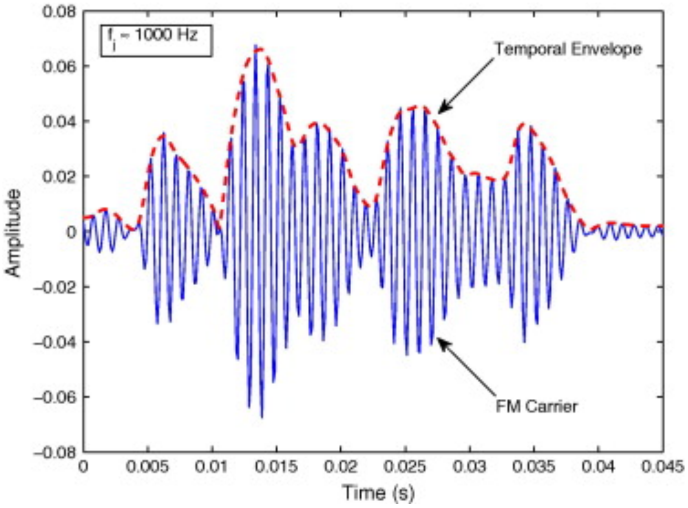


Figure 2. Example of the temporal envelope of speech (in red). (Image source: Sadjadi, S. O & Hansen, J. H. L. (2015). Mean Hilbert envelope coefficients (MHEC) for robust speaker and language identification. *Speech Communication*, 72, 138-148. https://doi.org/10.1016/j.specom.2015.04.005)

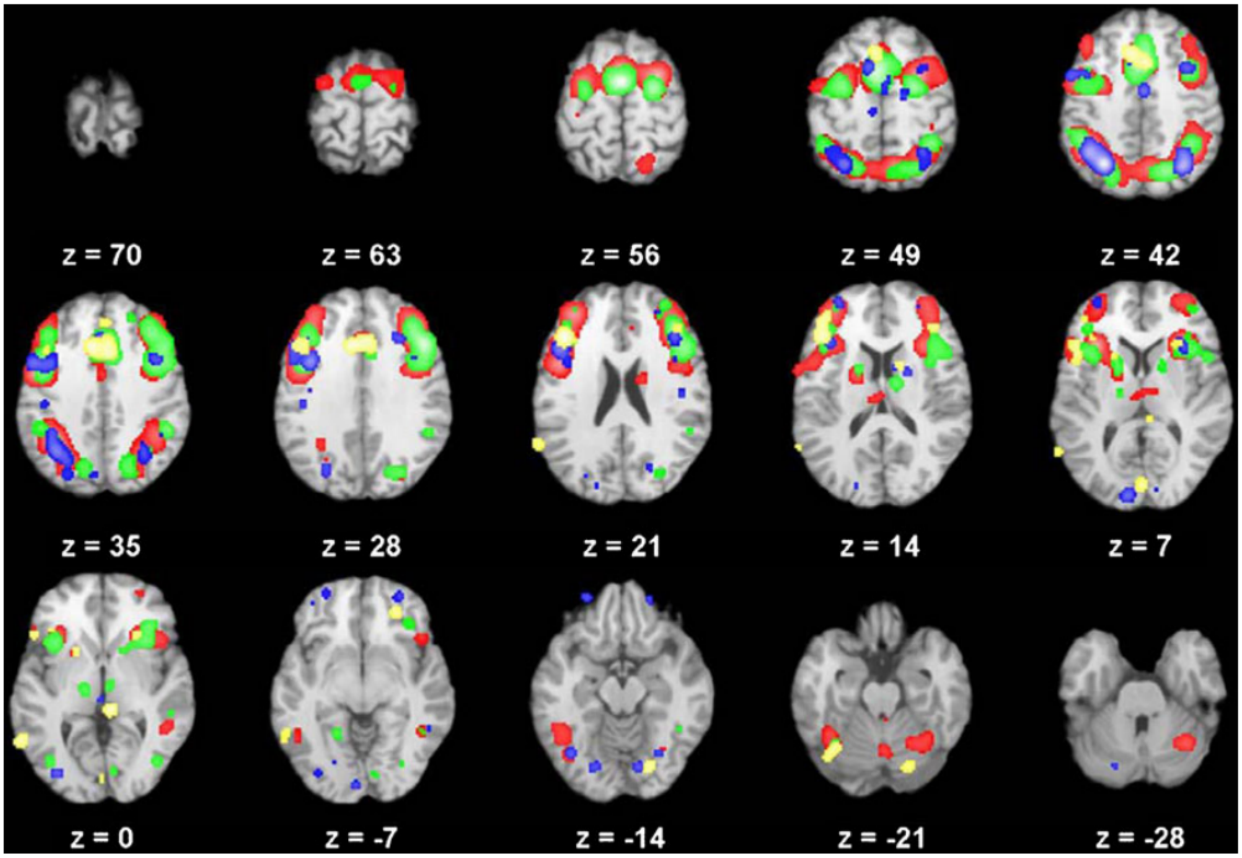


Figure 3. The cognitive control network. Activation during working memory (in red; from 78 studies), inhibition (in green; from 79 studies), flexibility (in blue; from 21 studies), and initiation (in yellow; from 9 studies) from a total of 2,832 healthy participants across 193 studies employing executive functioning experimental conditions compared against an active control condition during fMRI or PET. (Image source: Niendam, T.A., Laird, A.R., Ray, K.L., Dean, Y.M., Glahn, D.C., & Carter, C.S. (2012). Meta-analytic evidence for a superordinate cognitive control network subserving diverse executive functions. *Cogn. Affect. Behav. Neurosci.*, 12(2):241-68. doi: 10.3758/s13415-011-0083-5)

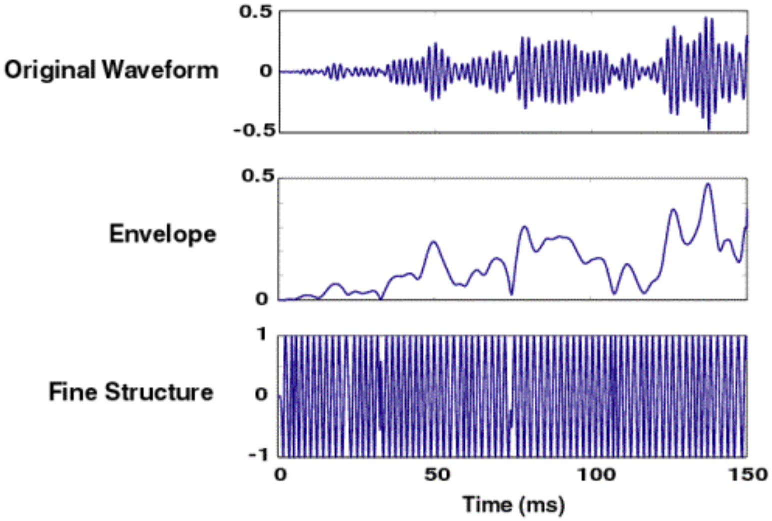


Figure 4. The complex original speech waveform can be separated into the temporal envelope and fine structure. The temporal envelope and fine structure each carry different information used for comprehending speech. (Image source: Wilson, B.S. & Forman, M. F. (2008). Cochlear implants: Current designs and future possibilities. *Journal of Rehabilitation Research & Development*, 45, 695-730).

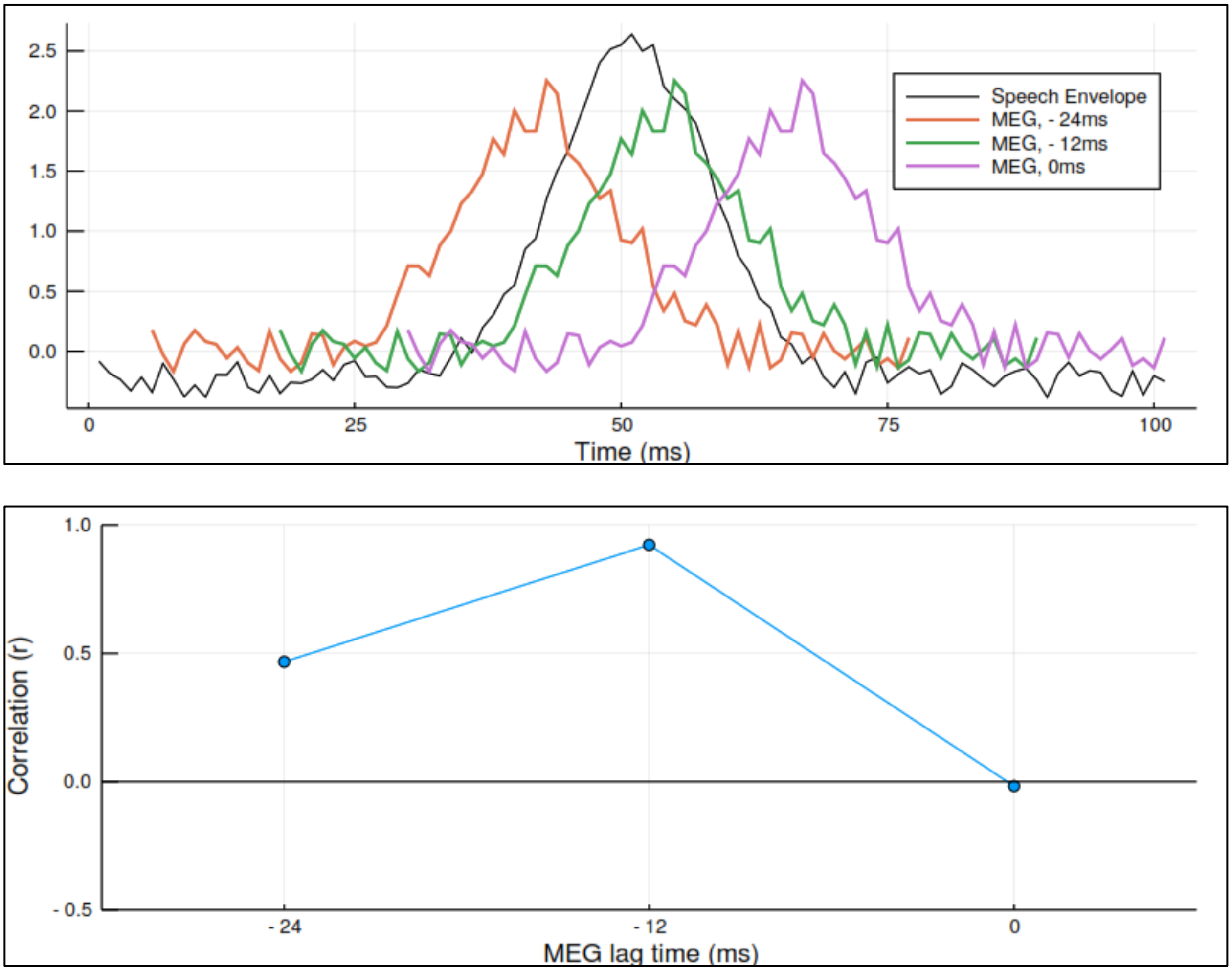


Figure 5. Simplified example of cross-correlation. The top graph shows two original signals, the speech envelope (in black) and the original MEG signal (in purple). Cross-correlation is calculated by sliding the function of the original MEG signal along the x-axis under the function of the speech envelope signal. The displaced MEG signal is illustrated at -12 ms (in green) and -24 ms (in orange). The integral of the multiplied functions is calculated at each position in order to determine how well the signals are correlated at each specified time lag, or displacement points. The bottom graph displays the correlations between the speech envelope and the MEG signal plotted at 0 ms, -12 ms, and -24 ms lag points. Note that the present study will use time lags of 0.5 ms for up to a 1000 ms phase-shift.

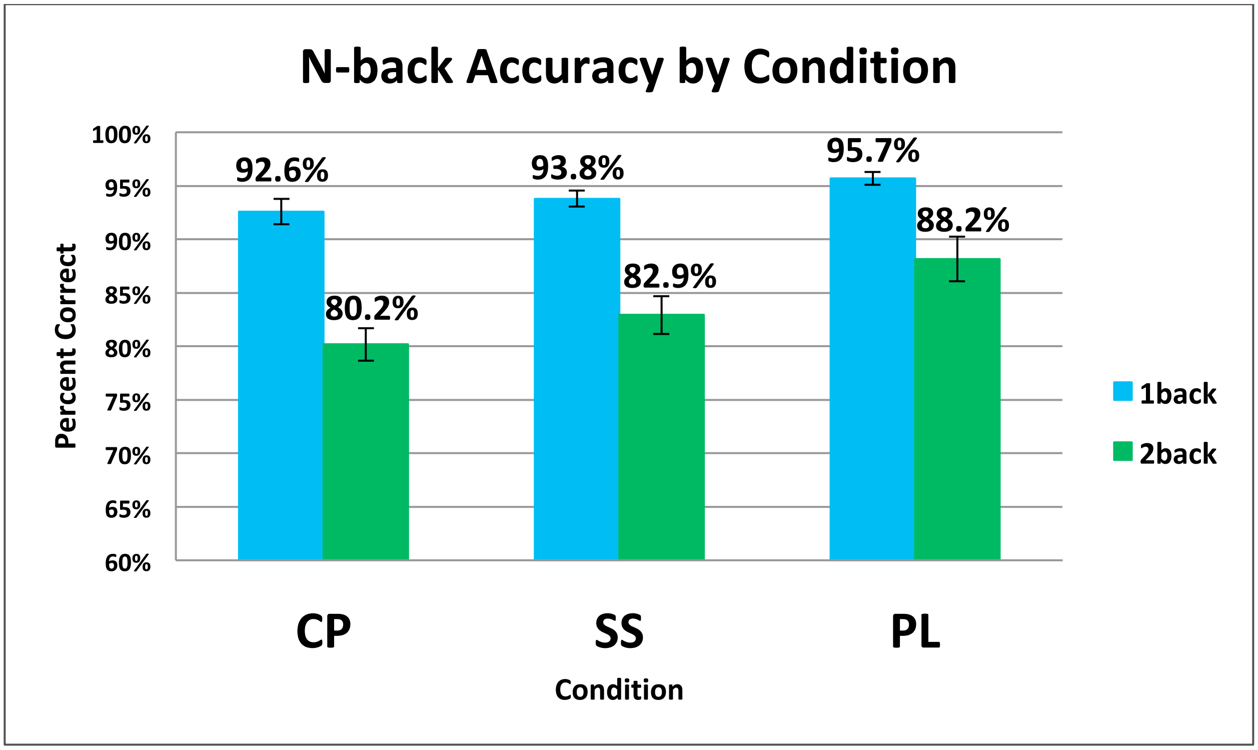


Figure 6. Behavioral performance comparison of n-back accuracy in each visual working memory load (1-back, 2-back) by auditory selective attention condition (CP, SS, PL). Error bars indicate standard error. CP = Cocktail Party; SS = Single Speaker; PL = Passive Listening.

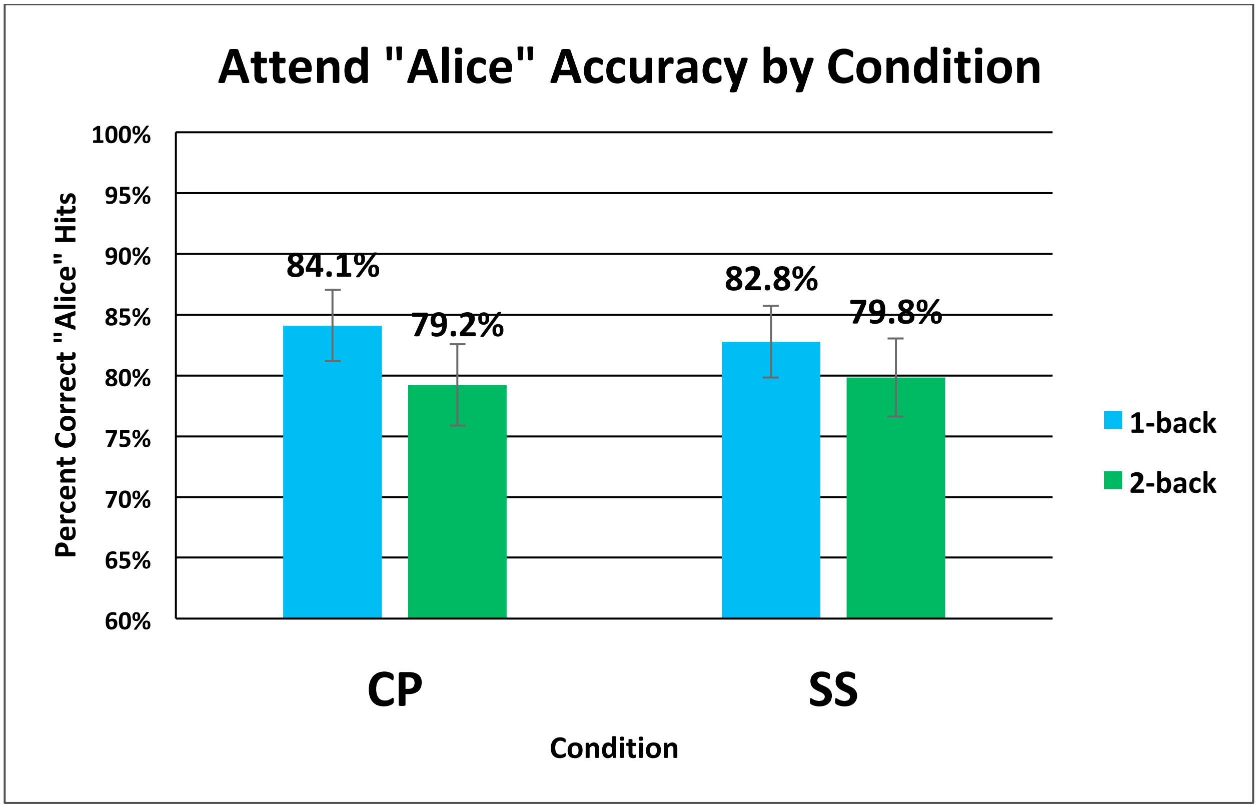
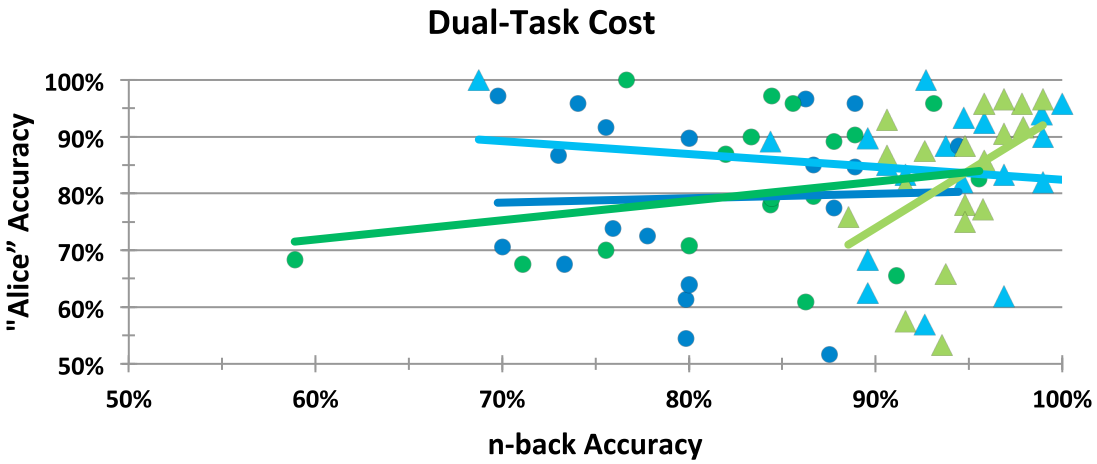


Figure 7. Behavioral performance comparison of "Alice" hit accuracy in the attended passage for each auditory selective attention condition with explicit attend passage assignment (CP, SS) by visual working memory load (1-back, 2-back). Error bars indicate standard error. CP = Cocktail Party; SS = Single Speaker.

(A)



(B)

Condition Comparison			z-score	*p* (2-tailed)*
SS-1 (*r* = 0.45)	vs.	SS-2 (*r* = 0.20)	0.77	0.4413
SS-1 (*r* = 0.45)	vs.	CP-1 (*r* = -0.12)	1.71	0.0873
SS-1 (*r* = 0.45)	vs.	CP-2 (*r* = 0.04)	1.25	0.2113
SS-2 (*r* = 0.20)	vs.	CP-1 (*r* = -0.12)	0.94	0.3472
SS-2 (*r* = 0.20)	vs.	CP-2 (*r* = 0.04)	0.47	0.6384
CP-1 (*r* = -0.12)	vs.	CP-2 (*r* = 0.04)	-0.46	0.6455

*Before Bonferroni correction for multiple comparisons, *p* = .05

Figure 8. (A). Dual-task cost by condition. (B). Differences in dual-task cost by condition. Fisher r-to-z transformation to compare significance of difference between Pearson correlation coefficients. No differences were observed in performance cost among dual-task conditions.

Note. ▲ SS-1 = Single Speaker 1-back
● SS-2 = Single Speaker 2-back
▲ CP-1 = Cocktail Party 2-back
● CP-2 = Cocktail Party 2-back

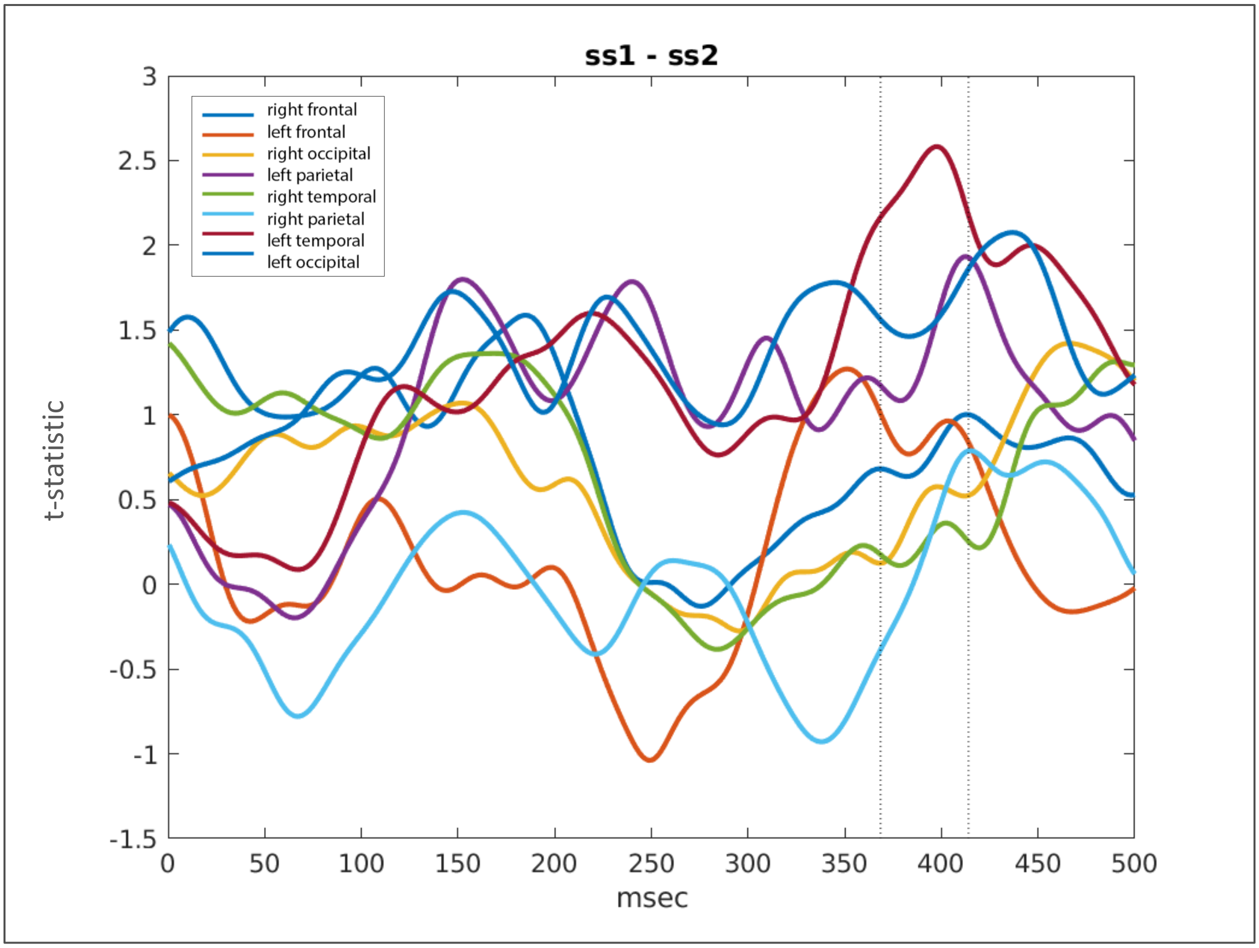


Figure 9. Effect of working memory load by ROI on neural entrainment to attended speech in the absence of competing noise [(Single Speaker 1-back) – (Single Speaker 2-back)]. Vertical dotted lines denote the significant time cluster (368.5 – 414 ms) of phase-locked neural firing to attended speech in the left temporal ROI. *Note*. x-axis = lag time in milliseconds; y-axis = t statistic value (threshold $t = 2.1$ for $p = .001$, corrected for multiple comparisons across ROI and time lags).

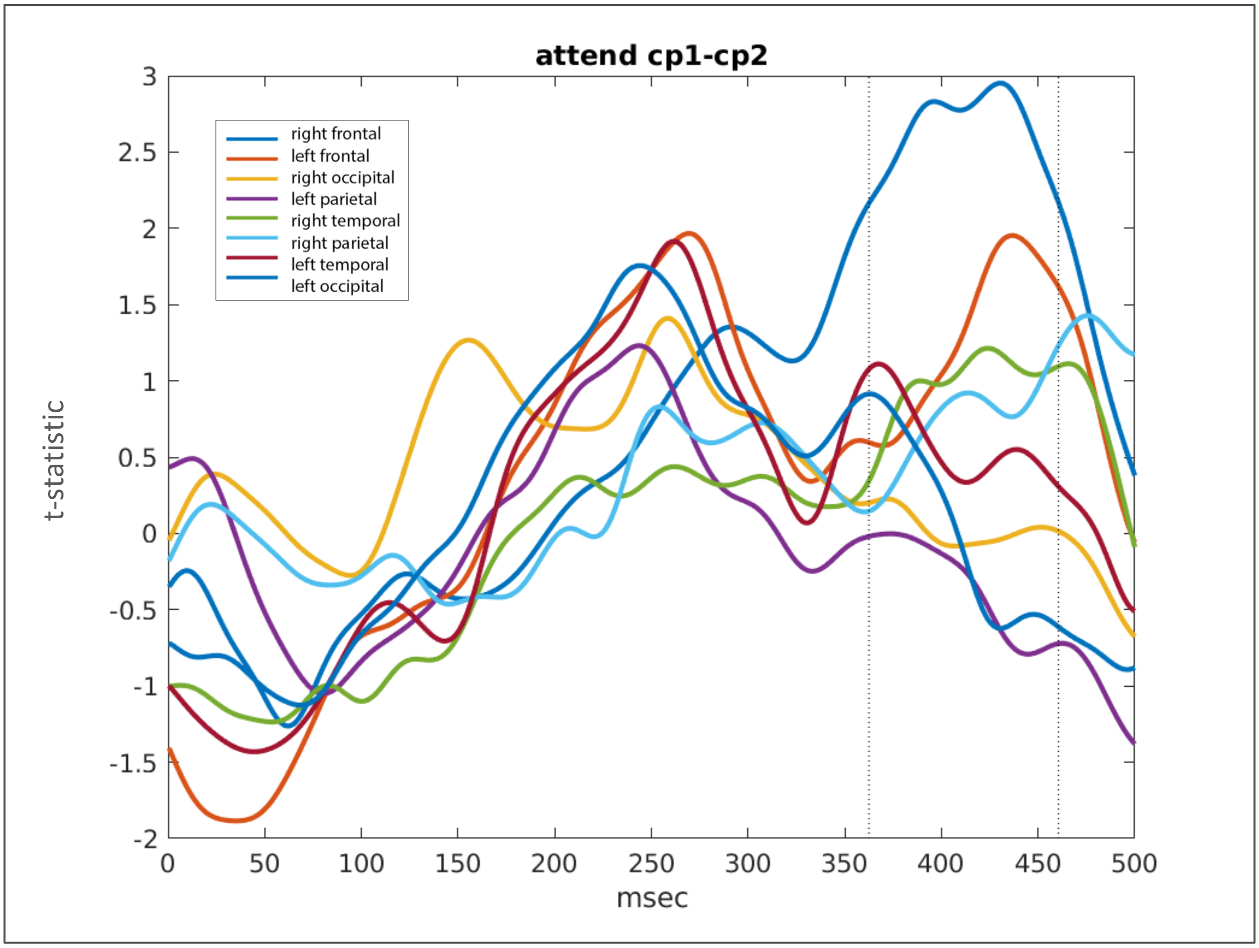


Figure 10. Effect of working memory load by ROI on neural entrainment to *attended* speech in the presence of competing noise [(Cocktail Party 1-back) – (Cocktail Party 2-back)]. Vertical dotted lines denote the significant time cluster (362.5 – 460.5 ms) of phase-locked neural firing to attended speech in the right frontal ROI. *Note*. x-axis = lag time in milliseconds; y-axis = t statistic value (threshold $t = 2.1$ for $p = .001$, corrected for multiple comparisons across ROI and time lags).

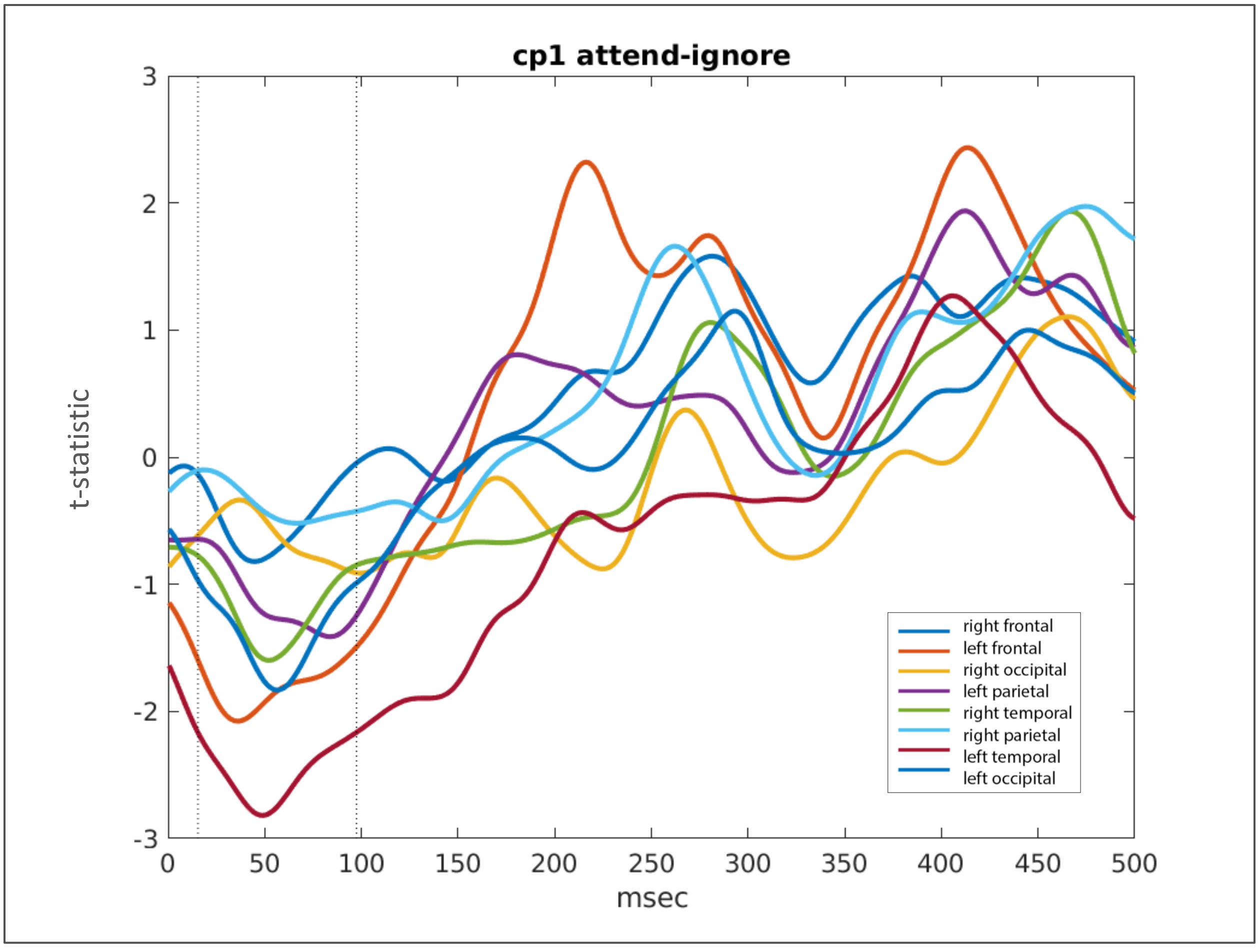


Figure 11. The difference in neural entrainment to attended and ignored speech when simultaneous visual working memory load is held constant [(Cocktail Party 1-back *attend*) – (Cocktail Party 1-back *ignore*)]. Vertical dotted lines denote the significant time cluster (15.5 – 97.5 ms) of phase-locked neural firing to ignored speech in the left temporal ROI. *Note*. x-axis = lag time in milliseconds; y-axis = t statistic value (threshold *t* = -2.1 for *p* = .001, corrected for multiple comparisons across ROI and time lags).

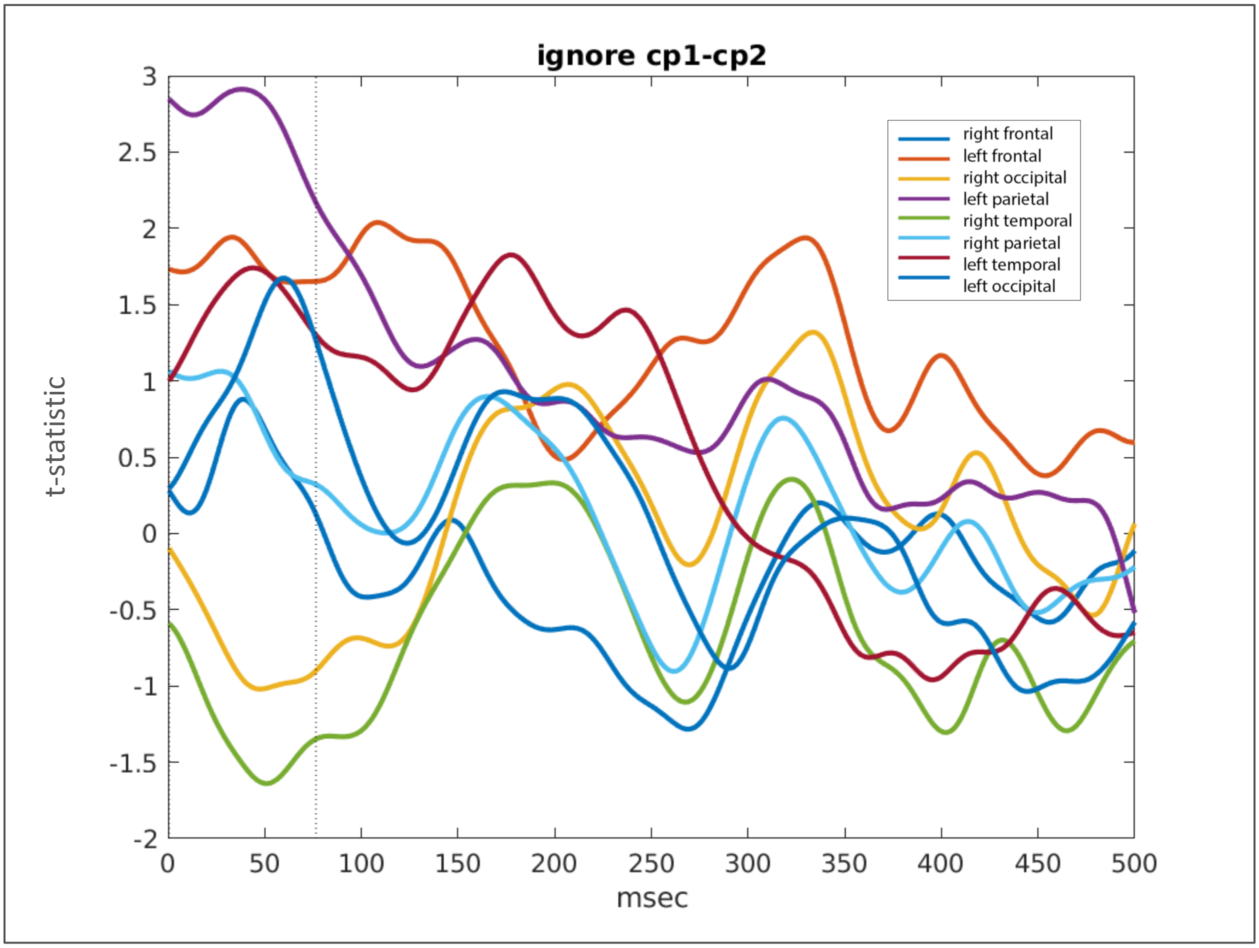
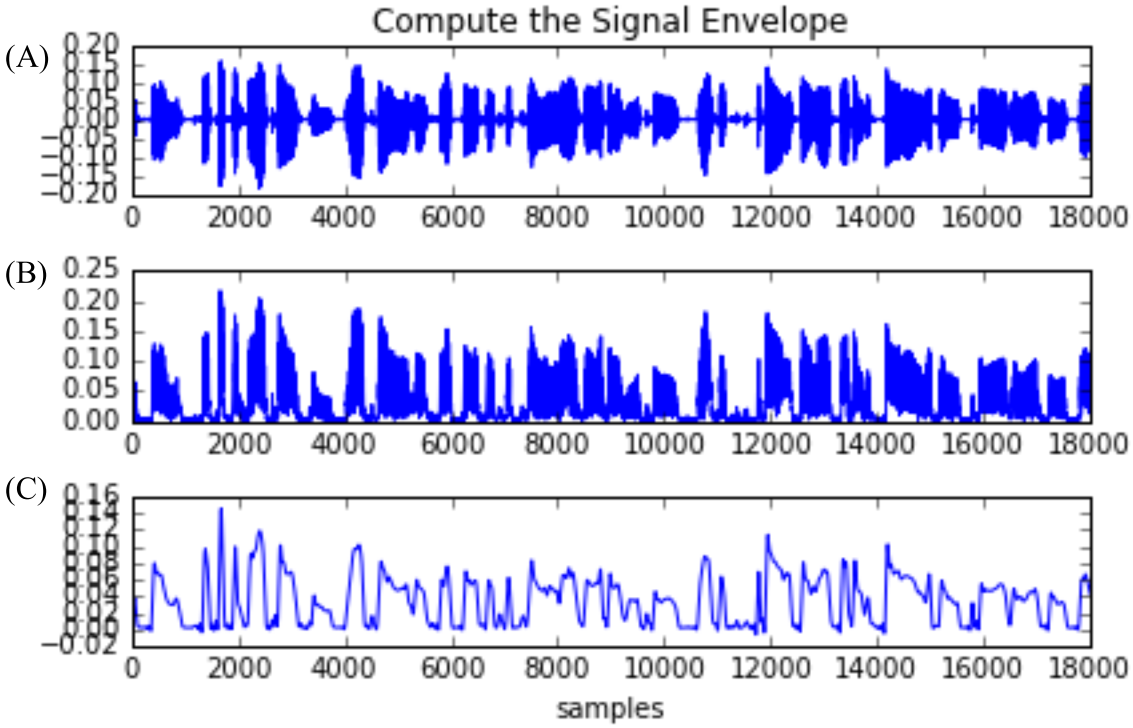
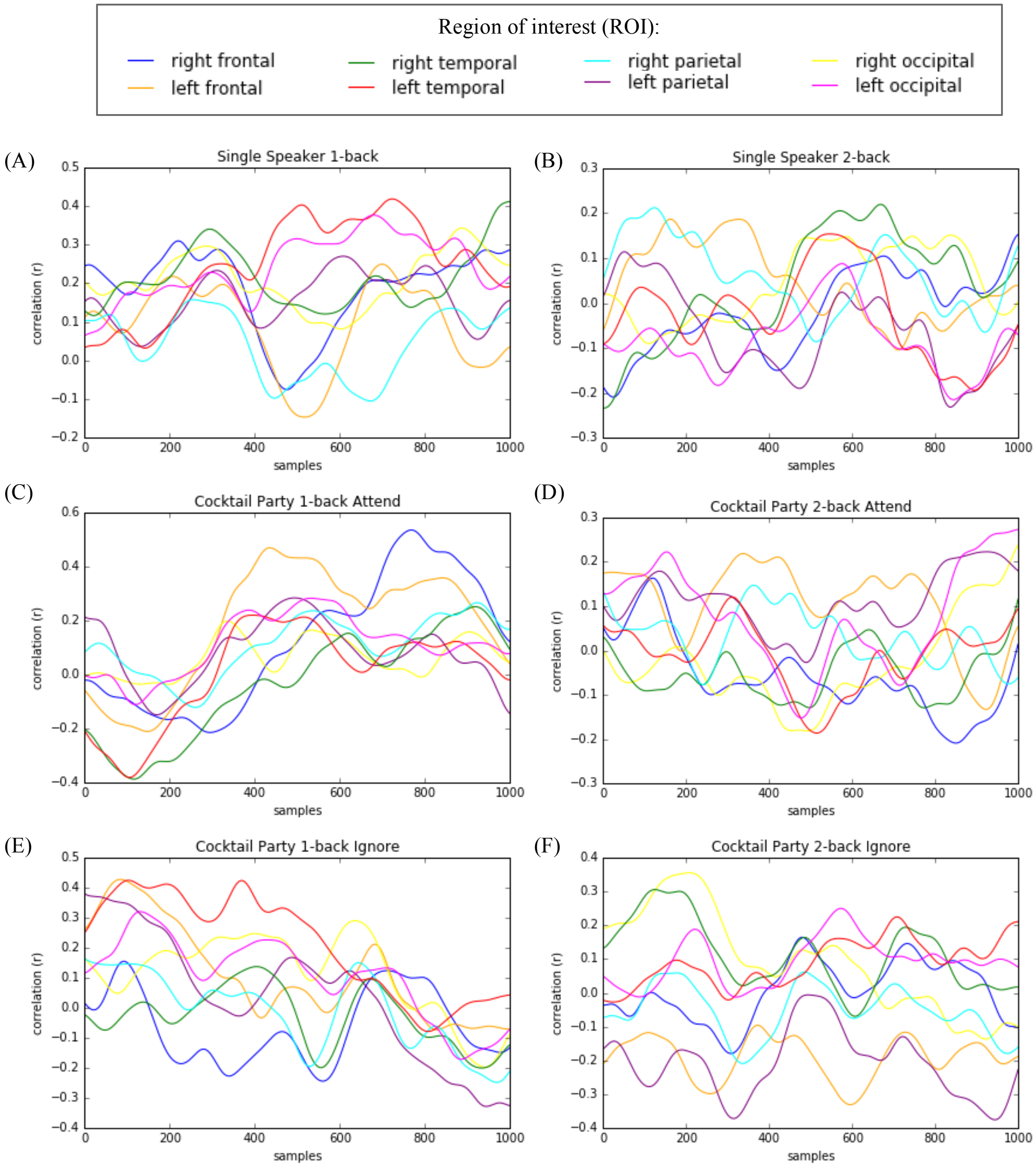


Figure 12. Impact of working memory load by ROI on neural entrainment for suppression of *ignored* speech [(Cocktail Party 1-back) – (Cocktail Party 2-back)]. Vertical dotted lines denote the significant time cluster (0.5 – 76.5 ms) of phase-locked neural firing to ignored speech in the left parietal ROI. *Note*. x-axis = lag time in milliseconds; y-axis = t statistic value (threshold t = 2.1 for p = .001, corrected for multiple comparisons across ROI and time lags).



Supplemental Figure 1. Steps to compute the signal envelope are depicted utilizing an attended speech passage segment of 9 seconds (equivalent to 18000 samples). The (A) raw signal is (B) Hilbert transformed and (C) filtered by removing the higher frequencies.

Cross-correlations of Attended and Ignored Speech by ROI per Condition



Supplemental Figure 2. Cross-correlations of attended and ignored speech envelopes by MEG signal ROI across a latency of 500 ms (equivalent to 1000 samples pictured above) and averaged across the 14 participants. (A) Single Speaker 1-back and (B) Single Speaker 2-back cross-correlations to the attended speech passages in the absence of auditory distraction; cross-correlations to the (C) attended and (E) ignored speech passages of the Cocktail Party 1-back condition; cross-correlations to the (D) attended and (F) ignored speech passages of the Cocktail Party 2-back condition.

CURRICULUM VITAE

Michelle Tamar Kassel

EDUCATION

7/2019 – 6/2020	**Warren Alpert Medical School of Brown University**, Providence, RI *Doctoral Psychology Internship*, Medical Neuropsychology Track Primary Supervisor: Geoffrey Tremont, Ph.D., ABPP-CN
9/2014 – 8/2020	**University of Wisconsin – Milwaukee**, Milwaukee, WI *Doctor of Philosophy*, Psychology, Clinical ***Dissertation**:* The impact of task load on neural entrainment to attended speech: A dual task magnetoencephalography (MEG) paradigm
5/2017	*Master of Science*, Psychology Primary Mentor: David Osmon, Ph.D., ABPP-CN
9/2006 – 5/2010	**University of Michigan**, Ann Arbor, MI *Bachelor of Arts*, Brain, Behavior & Cognitive Sciences Sub-concentration: Latin American & Caribbean Studies University Honors – 2009
1 – 6/2009	**Universidad Complutense de Madrid**, Madrid, Spain International Education of Students Abroad

FELLOWSHIPS AND AWARDS

2018 – 2019	**Distinguished Dissertation Fellowship,** University of Wisconsin - Milwaukee ($16,500) Awarded from the Graduate School for academic merit ($1000) Travel Award for professional development
2017 – 2018	**Distinguished Graduate Student Fellowship,** University of Wisconsin - Milwaukee ($15,000) Awarded from the Graduate School for academic merit ($1000) Travel Award for professional development
2018	**Association of Graduate Students in Neuropsychology Travel Award**, University of Wisconsin – Milwaukee ($1000)
2017	**Association of Graduate Students in Neuropsychology Travel Award**, University of Wisconsin – Milwaukee ($1000)
2016	**Graduate Student Travel Award**, University of Wisconsin – Milwaukee ($500)
2015	**Graduate Student Travel Award**, University of Wisconsin – Milwaukee ($500)

RESEARCH EXPERIENCE

7/2019 – 6/2020	**Doctoral Psychology Internship Research Rotation,** Warren Alpert Medical School of Brown University, Department of Cognitive Linguistic & Psychological Sciences Cognitive Neuroscience of Cognitive Control and Memory Laboratory David Badre, Ph.D., Director Collaborators: Stephen Correia, Ph.D., ABPP-CN, Nicole McLaughlin, Ph.D., Paul Malloy, Ph.D. *Cognitive Control in Gamma Knife Ventral Capsulotomy for Treatment of Obsessive-Compulsive Disorder*
9/2014 – 8/2020	**Graduate Student Research Trainee,** University of Wisconsin – Milwaukee, Department of Psychology Adult Neuropsychology Research Laboratory David Osmon, Ph.D., ABPP-CN, Director *Non-Gaussian Evaluation of Executive Function Components* (PI: David Osmon, Ph.D., ABPP-CN) Collaborative projects with Medical College of Wisconsin, Department of Neurology *Spatiotemporal Dynamics of Attention Control* (PI: Merav Sabri, Ph.D.) *Neural Mechanisms of Auditory Attention* (PI: Merav Sabri, Ph.D.)

4/2013 – 6/2014 **Research Coordinator**, University of Illinois at Chicago, Department of Education
Collaborative project with University of Houston, Department of Psychology
Bilingual Lyrical Mind (Co-PI: Aria Razfar, Ph.D. and Arturo Hernandez, Ph.D.)

9/2012 – 6/2014 **Research Specialist in Mental Health**, University of Illinois at Chicago, Department of Psychiatry
Multifaceted Explorations of the Neurobiology of Depressive Disorders (MEND2) Laboratory
Cognitive Neuroscience Center, Scott Langenecker, Ph.D., Director
I moved to University of Illinois at Chicago to continue working with Scott Langenecker, Ph.D. Several of the projects were shared between University of Michigan and University of Illinois at Chicago, with the University of Illinois at Chicago designated as the lead site.
§Continuing Projects Shared with University of Michigan: (*Primary Projects)
**Identification of Neurobiological Intermediate Phenotypes in Major Depressive Disorder* (PI: Scott Langenecker, Ph.D.)*; Depression Subtypes: Cognition, Emotion, and Neurophysiology* (PI: Scott Langenecker, Ph.D.); **Patterns of Brain Activation with Impaired Emotion Facial Perception in Depression and Related Psychological and Neurological Disorders* (PI: Scott Langenecker, Ph.D.); **Repeated Partial Sleep Deprivation to Augment SSRI Response in Depression* (PI: J. Todd Arnedt, Ph.D.)
Additional University of Illinois at Chicago Projects:
Mindfulness Intervention to Study the Neurobiology of Depression (PI: Rachel Jacobs, Ph.D.)

6/2010 – 6/2012 **Neuropsychology Research Technician Associate**, University of Michigan, Department of Psychiatry
MEND2 Laboratory, Scott Langenecker, Ph.D., Director
§*MEND2 Projects and Lab Responsibilities subsequently carried over to UIC are noted above.*
Additional University of Michigan Projects:
Investigation of Neuroanatomical Networks to Understand Late Onset Depression (Co-PIs: Sara Weisenbach, Ph.D. and Scott Langenecker, Ph.D.); **Phase-Specific Variability in Bipolar Disorder* (PI: Kelly Ryan, Ph.D.)
Collaborative work with *Translational Neuroimaging Laboratory*, Jon-Kar Zubieta, M.D., Ph.D., Director
Bipolar Disorder Study: Investigation of Novel Genes & Neuroimaging, Neuroendocrine & Neuropsychological Endophenotypes (PI: Jon-Kar Zubieta, M.D., Ph.D.)
Collaborative Projects with the Heinz C. Prechter Bipolar Research Fund
**Longitudinal Study of Bipolar Disorder* (PI: Melvin McInnis, M.D.); *Bipolar and Schizophrenia Network on Intermediate Phenotypes (BSNIP;* PI: Melvin McInnis, M.D.)
Collaborative Project with University of California-San Diego:
Pharmacogenomics of Mood Stabilizer Response in Bipolar Disorder (PGBD; PI: John Kelsoe, M.D.)

1 – 4/2010 **Undergraduate Research Assistant**, University of Michigan, Department of Psychology
Language and Cognitive Architecture Laboratory
Faculty Supervisor: Richard Lewis, Ph.D.

1 – 4/2010 **Undergraduate Research Assistant**, University of Michigan, Department of Psychology
Molecular and Behavioral Neuroscience Institute
Faculty Supervisor: Jill Becker, Ph.D.

7 – 8/2009 **Undergraduate Research Volunteer**, Hurley Medical Center, Department of Research

PEER REVIEWED PUBLICATIONS

Kassel, M.T., Rao, J.A., Walker, S.J., Briceño, E.M., Gabriel, L.B., Weldon, A.L., Avery, E.T., Haase, B.D., Peciña, M., Considine, C.M., Noll, D.C., Bieliauskas, L.A., Starkman, M., Zubieta, J-K., Welsh, R.C., Giordani, B., Weisenbach, S.L. & Langenecker, S.A. (2016). Decreased fronto-limbic activation and disrupted semantic cued list learning in Major Depressive Disorder. *Journal of International Neuropsychological Society*, 22, 1-14. doi: 10.1017/S1355617716000023.

Jenkins, L.M., **Kassel, M.T.**, Gabriel, L.B., Gowins, J., Hymen, E.A., Verges, A., Calamia, M., Crane, N.A., Jacobs, R.H., Ajilore, O., Welsh, R.C., Drevets, W.C., Phillips, M.L., Zubieta, J-K. & Langenecker, S.A. (2015). Amygdala and dorsomedial hyperactivity to emotional faces in youth with remitted Major Depression. *Social Cognitive and Affective Neuroscience*, 11(5), 736-45. doi:10.1093/scan/nsv15.

Schallmo, M.P., **Kassel, M.T.**, Walker, S.J., Weisenbach, S.L., Guidotti-Breting, L.M., Hazlett, K.E., Considine, C.M., Sethi, G., Vats, N., Peciña, M., Welsh, R.C., Starkman, M.N., Giordani, B. & Langenecker, S.A. (2015). A new semantic list learning task to parse the functioning of the Papez circuit. *Journal of Clinical and Experimental Neuropsychology*, 37(8), 816-33. doi: 10.1080/13803395.2015.

Rao, J., **Kassel, M.T.**, Weldon, A., Avery, E.A., Briceño, E., Mann, M., Cornett, B., Kales, H., Zubieta, J-K, Welsh, R.C., Langenecker, S.A. & Weisenbach, S.L. (2015). The double burden of age and Major Depressive Disorder on the cognitive control network. *Psychology and Aging*, 30(2), 475-85. doi: 10.1037/pag0000027.

Weisenbach, S.L., **Kassel, M.T.**, Rao, J.A., Weldon, A.L., Avery, E.T., Briceño, E.M., Mann, M.M., Kales, H.C., Welsh, R.C., Zubieta, J-K. & Langenecker, S.A. (2014). Differential prefrontal and subcortical circuitry engagement during encoding of semantically related words in patients with late-life depression. *International Journal of Geriatric Psychiatry*, 29(11), 1104-15. doi: 10.1002/gps.4165.

Peters, A.T., Smith, R.A., **Kassel, M.T.**, Hagan, M.J., Maki, P., Van Meter, A., Briceño, E.M., Ryan, K.A., Weldon, A.L., Weisenbach, S.L., Starkman, M.N. & Langenecker, S.A. (2018). A pilot investigation of differential neuroendocrine associations with fronto-limbic activation during semantically-cued list learning in mood disorders. *Journal of Affective Disorders*, 239, 180-191. doi: 10.1016/j.jad.2018.07.006.

Jenkins, L.M., Kendall, A., **Kassel, M. T.**, Patrón, V.G., Gowins, J.R., Dion, C., Shankman, S., Weisenbach, S.L., Maki, P. & Langenecker, S.A. (2018). Considering sex differences clarifies the effects of depression on facial emotion processing during fMRI. Journal of Affective Disorders, 225, 129-136. doi: 10.1016/j.jad.2017.08.027.

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Schreiner, M.W., DelDonno, S.R., Pocius, S., **Kassel, M.T.**, Skerrett, K.A., Kling, L.R., Stange, J.P., Jenkins, L.M. & Langenecker, S.A. (2020). Association between trauma and neural mechanisms of emotional face processing in young adults with versus without histories of self-injurious thoughts and behaviors. *Biological Psychiatry*, 87(9):S253-S254. doi: 10.1016/j.biopsych.2020.02.655.

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doi: 10.1007/s11065-018-9382-8.

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Osmon, D.C., Santos, O.A., Kazakov, D., **Kassel, M.T.**, Mano, Q.R. & Morth, A. (2018). Big Five personality relationships with general intelligence and specific Cattell-Horn-Carroll factors of intelligence. *Personality and Individual Differences*, 131, 51-56. doi: 10.1016/j.paid.2018.04.019

Weldon, A.L., Hagan, M.J., Van Meter, A., Jacobs, R.H., **Kassel, M.T.**, Hazlett, K.E., Haase, B.D., Vederman, A.C., Avery, E.T., Briceño, E.M., Welsh, R.C., Zubieta, J-K., Weisenbach, S.L. & Langenecker, S.A. (2015). Stress response to the fMRI environment in healthy adults relates to degree of limbic reactivity during emotion processing. *Neuropsychobiology*, 71(2), 85-96.

Crane, N.A., Gabriel, L.B., Meyers, K.K., Weldon, A.L., **Kassel, M.T.**, Marmelstein, R.J., Zubieta, J-K. & Langenecker, S.A. (2015). Shared and distinct neural mechanisms of inhibitory control in individuals with a history of Substance Use Disorder and depression. *Drug & Alcohol Dependence*, 156:e50-e51.

Hymen, E.A., Rao, J.A., Peters, A.T., Jenkins, L.M., Weisenbach, S.L., **Kassel, M.T.**, Farah, L.B., Skerrett, K.A., Haywood, J.T., Angers, K., Pester, B., Baker, A., Zubieta, J-K., Ryan, K.A. & Langenecker, S.A. (2019). Memory differences by sex, but not by previous diagnosis of major depressive disorder. Applied Neuropsychology: Adult. doi: 10.1080/23279095.2018.1496334

Crane, N.A., Verges, A., Kamali, M., Bhaumik, R., Ryan, K.A., Marshall, D.F., Saunders, E.F.H., **Kassel, M.T.**, Weldon, A.L., McInnis, M.G. & Langenecker, S.A. (2018). Developing dimensional, pandiagnostic inhibitory control constructs with self-report and neuropsychological data. *Assessment*, 1-16. doi: 10.1177/1073191118754704.

Peters, A.T., Van Meter, A., Pruitt, P.J., Briceño, E.M., Ryan, K.A., Hagan, M., Weldon, A.L., **Kassel, M.T.**, Vederman, A., Zubieta, J.K., McInnis, M., Weisenbach, S.L., & Langenecker, S.A. (2016). Acute cortisol reactivity attenuates engagement of fronto-parietal and striatal regions during emotion processing in negative mood disorders. *Psychoneuroendocrinology*, 73, 67-78. doi: 10.1016/j.psyneuen.2016.07.215.

Peters, A.T., Jacobs, R.H., Crane, N.A., Ryan, K.A., Weisenbach, S.L., Ajilore, O., Lamar, M., **Kassel, M.T.**, Gabriel, L.B., West, A.W., Zubieta, J-K. & Langenecker, S.A. (2015). Domain-specific impairment in cognitive control among remitted youth with a history of Major Depression. *Early Intervention in Psychiatry*. doi:10.1111/eip.12253.

PROFESSIONAL PRESENTATIONS

1. **Kassel, M.T.**, Humphries, C., Ustine, C.M.J., Gross, W., Osmon, D.C. & Sabri, M. Task load impacts selective attention to speech: A multitask paradigm in healthy adults. Poster presented at the 48th Annual Meeting of the International Neuropsychological Society, Denver, CO, February 2020.
2. **Kassel, M.T.**, Zolliecoffer, C., & Osmon, D.C. Construct Validity of the Conner's CPT Factors: Mental Speed, Working Memory and Inhibition. Poster presented at the 47th Annual Meeting of the International Neuropsychological Society, New York, NY, February 2019.
3. Zolliecoffer, C., **Kassel, M.T.** & Osmon, D.C. Jensen Box Reaction Times Do Not Differ Using a Dedicated Chip Compared to a Computer Operating System. Poster presented at the 47th Annual Meeting of the International Neuropsychological Society, New York, NY, February 2019.
4. **Kassel, M.T.**, Zolliecoffer, C., Kazakov, D. & Osmon, D.C. Differential Contributions of Executive Control to Predict Intelligence. Poster presented at the 38th Annual Meeting of the National Academy of Neuropsychology, New Orleans, LA, October 2018.
5. Zolliecoffer, C., **Kassel, M.T.**, Kazakov, D. & Osmon, D.C. Negative Priming Stroop Effect: Executive Control Added to Stroop Interference Effect. Poster presented at the 38th Annual Meeting of the National Academy of Neuropsychology, New Orleans, LA, October 2018.
6. Weisenbach, S.L., **Kassel, M.T.**, Rao, J., Welsh, R.C., Zubieta, J-K. & Langenecker, S.A. The Double Burden of Age and Disease on the Semantic Memory Network. Presented as part of a Symposium at the annual meeting of the American Association of Geriatric Psychiatry, Dallas, TX, March 2017.
7. **Kassel, M.T.**, Humphries, C., Altonji, K.A., Osmon, D.C. & Sabri, M. Radial Diffusivity of Cingulo-Opercular Network Predicts Attentional Switching Performance in Healthy Aging. Poster presented at the 45th Annual Meeting of International Neuropsychological Society, New Orleans, LA, February 2017.
8. Peters, A.T., Smith, R.A., **Kassel, M.T.**, Van Meter, A., Briceño, E.M., Ryan, K.A., Hagan, M.J., Weldon, A.L., Vederman, A.C., Zubieta, J-K., McInnis, M.G., Weisenbach, S.L., Starkman, M.N. & Langenecker, S.A. Neuroendocrine Modulation of Limbic Activation During Semantic List Learning in Depression. Poster presented at the 45th Annual Meeting of International Neuropsychological Society, New Orleans, LA, February 2017.
9. **Kassel, M.T.**, Humphries, C., Altonji, K.A., Osmon, D.C. & Sabri, M. White Matter Integrity of Executive Control Networks Predicts Selective Attention Performance in Healthy Aging. Poster presented at the 46th Annual Meeting of Society for Neuroscience, San Diego, CA, November 2016.
10. Athreya, A., Humphries, C., **Kassel, M.T.**, Altonji, K.A. & Sabri, M. Suppression Impairment in Aging during Bimodal Selective Attention. Poster presented at the 46th Annual Meeting of Society for Neuroscience, San Diego, CA, November 2016.
11. Feigon, M.S., **Kassel, M.T.**, Gabriel, L.B., Rao, J., Pocius, S., Ramahi, D. & Langenecker, S.A. Gender Differences in Emotional Valence on the Semantic List Learning Task. Poster presented at the 44th Annual Meeting of International Neuropsychological Society, Boston, MA, February 2016.
12. **Kassel, M.T.**, Humphries, C., Altonji, K.A., Hanson, J.L., Osmon, D.C. & Sabri, M. Structural Integrity of the Semantic Network is Associated with Selective Attention Performance across Age. Poster presented at the 7th Annual Meeting of Society for the Neurobiology of Language, Chicago, IL, October 2015.
13. Altonji, K.A., Hanson, J.L., **Kassel, M.T.**, Humphries, C. & Sabri, M. Neuropsychological and Neuroanatomical Factors Associated with Speech-in-Noise Perception in Aging. Poster presented at the 45th Annual Meeting of Society for Neuroscience, Chicago, IL, October 2015.
14. Crane, N.A., Gabriel, L.B., Meyers, K.K., Weldon, A.L., **Kassel, M.T.**, Mermelstein, R.J., Zubieta, J.K., & Langenecker, S.A. Shared & Distinct Neural Mechanisms of Inhibitory Control in Individuals with a History of a Substance Use Disorder & Depression. Poster presented at the 77th Annual Meeting of the College on Problems

of Drug Dependence, Phoenix, AZ, June 2015.

15. Crane, N.A., Jenkins, L.M., Gowins, J.R., Barba, A.M., Gabriel, L.B., **Kassel, M.T.**, Weldon, A.L., Baker, A.M., DelDonno, S.R., Zubieta, J.K., Mermelstein, R.J. & Langenecker, S.A. History of Substance Use Disorder Modulates Neural Emotional Processing in Individuals with Remitted Major Depression. Poster presented at the 70th Annual Meeting of Society of Biological Psychiatry, Toronto, Ontario, Canada, May 2015
16. Jenkins, L.M., Skerrett, K., Crane, N.A., Gowins, J.R., Patrón, V.G., Dion, C., **Kassel, M.T.**, Weldon, A.L., Gabriel, L.B., Weisenbach, S.L., Zubieta, J-K., Passarotti, A. & Langenecker, S.A. Decreased Neural Activity During Successful and Unsuccessful Cognitive Control in Remitted Major Depressive Disorder. Poster presented at the 70th Annual Meeting of Society of Biological Psychiatry, Toronto, Ontario, Canada, May 2015.
17. Rao, J.A., **Kassel, M.T**., Zubieta, J-K., Welsh, R.C., Langenecker, S.A. & Weisenbach, S.L. Cognitive Control Network Disruption and its Relationship with Grey Matter Volume in Late Life Depression. Poster presented at the 43rd Annual Meeting of International Neuropsychological Society, Denver, CO, February 2015.
18. Jenkins, L.M., Barba, A., **Kassel, M.T.**, Crane, N., Verges, A., Calamia, M., Gabriel, L.B., Hymen, E., Weisenbach, S.L., Maki, P. & Langenecker, S.A. Differential Brain Activation in Males and Females in the Remitted Phase of Major Depressive Disorder. Poster presented at the 28th Annual Meeting of Society for Research in Psychopathology, Evanston, IL, September 2014.
19. Gowins, J.R., Jenkins, L.M, Jacobs, R.H., Gabriel, L.B., **Kassel, M.T.**, Hymen, E.A., Barba, A.M., Bhaumik, R., Ajilore, O. & Langenecker, S.A. Young adults with remitted major depressive disorder demonstrate hyperactivations in regions of the emotional salience and cognitive control networks during the accurate perception of emotional faces. Poster presented at the 28th annual meeting of the Society for Research in Psychopathology, Evanston, IL, September 2014.
20. Crane, N.A., Barba, A.M., Gabriel, L.B., Weldon, A.L., Baker, A.M., Nagel, C.E., **Kassel, M.T.**, Hymen, E.A., Ryan, K.A., Mickey, B.J., Zubieta, J.K., & Langenecker, S.A. History of Substance Use Disorder Modulates Reward Processing Depending on Depression State. Poster presented at the 69th Annual Meeting for Society of Biological Psychiatry, New York, NY, May 2014.
21. Rao, J.A., **Kassel, M.T.**, Weldon, A.L., Avery, E.T., Briceño, E.M., Mann, M.M., Cornett, B., Kales, H.C., Zubieta, J-K., Langenecker, S.A. & Weisenbach, S.L. Depression and Aging Interact in Producing Aberrant Activation of Frontostriatal Circuits in Major Depressive Disorder. Poster presented at the 42nd Annual Meeting of International Neuropsychological Society, Seattle, WA, February 2014.
22. Jenkins, L.M., **Kassel, M.T.**, Gabriel, L.B., Hymen, E.H., Verges, A., Calamia, M., Crane, N.A., Jacobs, R.H., Ajilore, O., Welsh, R.C. & Langenecker, S.A. Hyperactivation and Hyperconnectivity of the Emotional Salience Network are Associated with Intact Facial Emotion Perception in Young Adults with Remitted Major Depressive Disorder. Poster presented at the 42nd Annual Meeting of International Neuropsychological Society, Seattle, WA, February 2014.
23. Briceño, E.M., Rapport, L.J., **Kassel, M.T.**, Weldon, A.L., Bieliauskas, L.A., Zubieta, J-K., Weisenbach, S.L. & Langenecker, S.A. Unique and Divergent Neural Activation Associated with Better and Poorer Emotion Perception in Healthy Adults. Poster presented at the 42nd Annual Meeting of International Neuropsychological Society, Seattle, WA, February 2014.
24. Walter, J., Avery, E.T., **Kassel, M.T.**, Gabriel, L.B., Weldon, A.L., Mann, M.M., Laurent, A.R., Briceño, E.M., Zubieta, J-K., Langenecker, S.A. & Weisenbach, S.L. Middle Aged Adults with MDD Demonstrate More Pronounced Cognitive Deficits than Younger and Older Adults with MDD, Relative to Same Age Peers. Poster presented at the 42nd Annual Meeting of International Neuropsychological Society, Seattle, WA, February 2014.
25. Crane, N.A., Kamali, M., Ryan, K.A., Marshall, D.F., Saunders, E.F.H., **Kassel, M.T.**, Weldon, A.L., McInnis, M.G., & Langenecker, S.A. Developing Dimensional, Integrated Constructs of Self-Report and Performance Data for Inhibitory Control. Poster presented at the 42nd Annual Meeting of International Neuropsychological Society, Seattle, WA, February 2014.
26. Langenecker, S.A., Jacobs, R.H., Crane, N.A., Ryan, K.A., Weisenbach, S.L., Ajilore, O., **Kassel, M.T.**, Gabriel, L.B., Zubieta, J-K. Reduced Impairment, Yet Increased Reliability of Cognitive Control Measurements in Remitted MDD. Poster presented at the 52nd Annual Meeting for American College of Neuropsychopharmacology, Hollywood, FL, December 2013.
27. Weisenbach, S.L., **Kassel, M.T.**, Avery, E.T., Kales, H.C., Heidebrink, J.L, Welsh, R.C., Zubieta, J-K. & Langenecker, S.A. Memory and Executive Functioning Loss and their Neurobiological Correlates Among Older Adults with Major Depressive Disorder. Symposium presented at the 52nd Annual Meeting for American College of Neuropsychopharmacology, Hollywood, FL, December 2013.

28. Weisenbach, S.L., **Kassel, M.T.**, Rao, J.A., Weldon, A.L., Avery, E.T., Briceño, E.M., Mann, M.M., Kales, H.C., Welsh, R.C., Zubieta, J-K. & Langenecker, S.A. Inefficiencies of Prefrontal and Subcortical Circuitry During Encoding of Novel Words in Patients with Late Life Depression. Poster presented at 13th Annual Meeting for International College of Geriatric Psychoneuropharmacology, Pittsburgh, PA, October 2013.
29. **Kassel, M.T.**, Walker, S.J., Weisenbach, S.L., Haase, B.D., Peciña, M., Considine, C.M., Noll, D.C., Zubieta, J-K. & Langenecker, S.A. Decreased Front-Limbic Activation and Disrupted Semantic Memory in Major Depressive Disorder (MDD). Poster presented at the 19th Annual Meeting of the Organization for Human Brain Mapping, Seattle, WA, June 2013.
30. Gabriel, L.B., Weisenbach, S.L., Ryan, K.A., Harrington, G.J., Weldon, A.L., **Kassel, M.T.**, King, C.A., Welsh, R.C., Johnson, T.D., Zubieta, J-K. & Langenecker, S.A. Stable Emotion Processing Deficits in Young Individuals with Remitted Depression. Poster presented at the 19th Annual Meeting of the Organization for Human Brain Mapping, Seattle, WA, June 2013.
31. Briceño, E.M., Rapport, L.J., Weisenbach, S.L., Ryan, K.A., **Kassel, M.T.**, Gabriel, L.B. & Langenecker, S.A. Normative Data for the Facial Emotion Perception Task. Poster presented at the 11th Annual American Academy of Clinical Neuropsychology Conference, Chicago, IL, June 2013.
32. Weisenbach, S.L., **Kassel, M.T.**, Avery, E.T., Cornett, B., Mann, M.M., Kales, H.C., Heidebrink, J.L., Zubieta, J-K. & Langenecker, S.A. Frontostriatal and Hippocampal Network Dysfunction among Patients with Late Life Depression. Symposium presented at the 68th Annual Meeting for Society of Biological Psychiatry, San Francisco, CA, May 2013.
33. Kay, R.E., Rapport, L.J., Weisenbach, S.L., **Kassel, M.T.**, Laurent, A.R., Bieliauskas, L.A., Giordani, B., Zubieta, J-K. & Langenecker, S.A. Effects of Psychotropic Medications upon Depression-Related Cognitive Decrements. Poster presented at the 41st Annual Meeting of International Neuropsychological Society, Waikoloa, HI, February 2013.
34. Langenecker, S.A., Ryan, K.A., Marshall, D.F., Gabriel, L.B., Weldon, A.L., **Kassel, M.T.**, Crane, N., Weisenbach, S.L. & Zubieta, J-K. Strong Reliability for Intermediate Phenotypes in the Multifaceted Investigation of the Neurobiology or Depression Subtypes (MINDS) Study. Symposium presented at the 41st Annual Meeting of International Neuropsychological Society, Waikoloa, HI, February 2013.
35. Weisenbach, S.L., Cornett, B., Mann, M.M., Haase, B.D., Avery, E.T., **Kassel, M.T.**, Kales, H., Heidebrink, J., Zubieta, J-K. & Langenecker, S.A. Frontostriatial and Hippocampal Network Dysfunction among Older Adults with Major Depressive Disorder. Symposium presented at the 41st Annual Meeting of International Neuropsychological Society, Waikoloa, HI, February 2013.
36. Weisenbach, S. L., Cornett, B., Haase, B.D., **Kassel, M.T**., Avery, E.T., Zubieta, J-K. & Langenecker, S.A. Frontostriatial Activation Abnormalities during Sustained Attention and Inhibitory Control among Patients with Late Life Depression. Poster presented at American College of Neuropsychopharmacology, Hollywood, FL, December 2012.
37. Weisenbach, S.L., Mann, M.M., **Kassel, M.T.**, Avery, E.T., Briceño, E.M., Haase, B.D., Kales, H.C., Heidebrink, J.L., Zubieta, J-K. & Langenecker, S.A. Hippocampal and HPA-Axis Functioning in Late Life Depression. Poster presented at National Network of Depression Centers Annual Meeting, Rochester, MN, November 2012.
38. Langenecker, S.A., Ryan, K.A., Vederman, A.C., Dawson, E., Marshall, D.F., Weldon, A.L., **Kassel, M.T.**, Weisenbach, S.L., Giordani, B., McInnis, M.G. & Zubieta, J-K. Shared and Specific Dimensions of Executive Dysfunction Across Mood Disorders. Poster presented at the 67th Annual Meeting for Society of Biological Psychiatry, Philadelphia, PA, May 2012.
39. Weisenbach, S.L., Haase, B.D., **Kassel, M.T.**, Peciña, M., Walker, S.J., Heidebrink, J.L., Zubieta, J-K., Kales, H.C. & Langenecker, S.A. Hippocampal Activation Abnormalities during Verbal Encoding Among Patients with Geriatric Depression. Poster presented at American Association for Geriatric Psychiatry Annual Meeting, Washington, D.C., March 2012.
40. Gabriel, L.B., Harrington, G.J., Weisenbach, S.L., Ryan, K.A., Weldon, A.L., **Kassel, M.T.**, Murnane, S.E., King, C.A., Wlesh, R.C., Johnson, T.D., Zubieta, J-K. & Langenecker, S.A. Identifying Traits and Predictors of Relapse Early in the Course of Major Depressive Disorder (MDD). Poster presented at the 10th Annual Meeting of Depression on College Campuses, Ann Arbor, MI, March 2012.
41. **Kassel, M.T.**, Walker, S.J., Weisenbach, S.L., Haase, B.D., Peciña, M., Considine, C.M., Noll, D.C., Langenecker, S.A. & Zubieta, J-K. Differential Impact of Distraction in Serial Position Curves with the Semantic List Learning Task (SLLT) in Women with and without Major Depressive Disorder (MDD). Poster presented at 40th Annual Meeting of International Neuropsychological Society, Montréal, Québec, Canada, February 2012.

42. Gabriel, L.B., Meyers, K.M., Weldon, A.L., Haase, B.D., **Kassel, M.T.**, Walker, S. J., Hsu, D. T., Noll, D. C., Mickey, B. J., Zubieta, J-K. & Langenecker, S. A. To Go or Not to Go? Differential Activation During Response Inhibition in Major Depressive Disorder. Poster presented at the 40th Annual Meeting of the International Neuropsychological Society, Montreal, CAN, February 2012.
43. Swanson, L., Langenecker, S.A., **Kassel, M.T.**, Hoffman, R., Armitage, R. & Arnedt, J.T. Effects of Partial Sleep Deprivation on Cognitive Performance in Major Depressive Disorder. Poster presented at the 25th Annual Meeting of the Associated Professional Sleep Societies, Minneapolis, MN, June 2011.
44. Ryan, K.A., Vederman, A.C., Langenecker, S.A., Weldon, A.L., **Kassel, M.T.**, Haase, B.D., Kamali, M. & McInnis, M.G. Occupational Disability in Bipolar Disorder Related to Cognitive Factors. Poster presented at the 66th Annual Meeting for Society of Biological Psychiatry, San Francisco, CA, May 2011.
45. **Kassel, M.T.**, Walker, S.J., Wright, S.L., Peciña, M., Considine, C.M., Noll, D.C., Langenecker, S.A. & Zubieta, J-K. Learning and Memory Differences among Women with and without Major Depressive Disorder (MDD). Poster presented at the 4th World Congress on Women's Mental Health, Madrid, Spain, March 2011.

PEER REVIEW EXPERIENCE

2017 **Ad-hoc manuscript reviewer** for *Assessment*

SUPERVISED CLINICAL EXPERIENCE

7/2019 – 6/2020 **Doctoral Psychology Internship in Clinical Neuropsychology,** Alpert Medical School, Brown University
Adult Clinical Neuropsychology Resident
Rhode Island Hospital and Providence VA Medical Center
Supervisors: Geoffrey Tremont, Ph.D., ABPP-CN, Jennifer Davis, Ph.D., ABPP-CN, Seth Margolis, Ph.D., Megan Spencer, Ph.D., Donald Labbe, Ph.D.

7/2019 – 6/2020 **Doctoral Psychology Internship in Clinical Neuropsychology,** Alpert Medical School, Brown University
Psychotherapy Resident, Aging Families and Caregiver Program
Rhode Island Hospital
Supervisor: Thomas Sheeran, Ph.D.

6/2018 – 5/2019 **Neuropsychology Extern,** Clement J. Zablocki VA Medical Center, Department of Psychology
Neuropsychology, Adult
Supervisors: Eric Larson, Ph.D., ABPP-CN, Angela Gleason, Ph.D., ABPP-CN, Kathleen Patterson, Ph.D., ABPP-CN

9/2018 – 5/2019 **Neuropsychology Extern,** Columbia St. Mary's Hospital, Sacred Heart Rehabilitation Institute
Brain Injury Day Treatment Program
Supervisor: David Osmon, Ph.D., ABPP-CN

9/2017 – 5/2019 **Neuropsychometrist,** University of Wisconsin - Milwaukee, Department of Psychology
Retired NFL Football Players Baseline Assessment Program
Supervisor: David Osmon, Ph.D., ABPP-CN

9/2017 – 6/2018 **Neuropsychology Graduate Trainee,** University of Wisconsin – Milwaukee, Department of Psychology
Child Neuropsychology Clinic
Supervisor: Bonnie Klein-Tasman, Ph.D.

1/2018 – 6/2018 **Group Therapy Graduate Trainee,** University of Wisconsin – Milwaukee, Department of Psychology
Body Image Psychotherapy Group, Adolescent and Adult
Supervisor: Stacey Nye, Ph.D., FAED

5/2017 – 5/2018 **Neuropsychology Extern,** Medical College of Wisconsin, Department of Neurology
Division of Neuropsychology, Adult
Supervisors: Michael McCrea, Ph.D., ABPP-CN, Sara Swanson, Ph.D., ABPP-CN, David Sabsevitz, Ph.D., ABPP-CN, Julie Bobholz, Ph.D., ABPP-CN, Laura Umfleet, Psy.D. & Lindsay Nelson, Ph.D.

6/2016 – 8/2017 **Graduate Student Project Assistant,** University of Wisconsin - Milwaukee, Department of Psychology
Learning Disabilities Specialty Clinic

Supervisor: David Osmon, Ph.D., ABPP-CN

9/2016 – 5/2017 **Graduate Student Trainee,** University of Wisconsin - Milwaukee, Department of Psychology
Practicum in Psychotherapy
Supervisors: Stacey Nye, Ph.D., FAED and Robyn Ridley, Ph.D.

9/2015 – 5/2016 **Graduate Student Trainee,** University of Wisconsin - Milwaukee, Department of Psychology
Practicum in Clinical Assessment
Supervisors: Han Joo Lee, Ph.D. and Kristin Smith, Ph.D.

9/2014 – 5/2016 **Graduate Student Trainee,** University of Wisconsin - Milwaukee, Department of Psychology
1–5/2016 *Integrative Behavioral Couples Therapy Vertical Team*, Supervisor: Christopher Martell, Ph.D.
9–12/2015 *Child Anxiety Vertical Team*, Supervisor: Bonita Klein-Tasman, Ph.D.
1–5/2015 *Behavioral Activation Vertical Team*, Supervisor: Christopher Martell, Ph.D.
9–12/2014 *Generalist Vertical Team*, Supervisor: Robyn Ridley, Ph.D.

SPECIALIZED TRAINING EXPERIENCES

2017 – 2019 **Cases in Clinical Neuropsychology Seminar Series,** University of Wisconsin - Milwaukee
Faculty Supervisor: Krista Lisdahl, Ph.D.

2017 – 2018 **Neuropsychology Journal Club,** Medical College of Wisconsin
Presenters: Neurology Departmental faculty and post-doctoral fellows

2017 – 2018 **Neuropsychology Seminar Series,** Medical College of Wisconsin
Lecturers: Neurology Departmental faculty and post-doctoral fellows

Summer 2017 **Group Therapy Workshop Series,** University of Wisconsin - Milwaukee
Lecturer: Stacey Nye, Ph.D., FAED

2016 – 2017 **MEG Data Processing Lecture Series,** Medical College of Wisconsin
Facilitator: Jeffrey Stout, Ph.D.

Fall 2017 **Transgender Mental Health Workshop,** University of Wisconsin - Milwaukee
Facilitator: Paul Dupont, Ph.D.
Invited Lecturer: Barry Schreier, Ph.D., University of Iowa

Fall 2016 **Eating Disorders Seminar Series,** University of Wisconsin - Milwaukee
Lecturer: Stacey Nye, Ph.D., FAED

Spring 2016 **Behavioral Activation for Depression Seminar,** University of Wisconsin - Milwaukee
Lecturer: Christopher Martell, Ph.D., ABPP

TEACHING EXPERIENCE

10/2016; 10/2017 **Guest Lecturer,** University of Wisconsin - Milwaukee, Department of Psychology
Practicum in Clinical Assessment (Graduate level course)
Topic: Neuropsychological Assessment of Learning Disorders and ADHD
Professor: Bonnie Klein-Tasman, Ph.D., Han Joo Lee, Ph.D., Kristin Smith, Ph.D.

9/2015– 5/2016 **Graduate Teaching Assistant,** University of Wisconsin - Milwaukee, Department of Psychology
Psychopathology, online course
Professor: Robyn Ridley, Ph.D.

1 – 5/2015 **Graduate Teaching Assistant,** University of Wisconsin - Milwaukee, Department of Psychology
Grading for the following undergraduate courses:
Neuropsychology, Nicole Nowak-Saenz, Ph.D.; *Perception*, Adam Greenberg, Ph.D.;
Health Psychology, Gary Stark, Ph.D.; *Psychopathology*, Gary Stark, Ph.D.

9 – 12/2014 **Graduate Teaching Assistant,** University of Wisconsin - Milwaukee, Department of Psychology
U-Pace Introduction to Psychology, online course
Professors: Diane Reddy, Ph.D. and Raymond Fleming, Ph.D.

LEADERSHIP AND SERVICE

2018 – 2019 **Association of Graduate Students in Neuropsychology,** University of Wisconsin – Milwaukee
Association of Neuropsychology Students in Training (ANST) Interest Group
President

2017 – 2018 **Association of Graduate Students in Neuropsychology,** University of Wisconsin – Milwaukee

	Association of Neuropsychology Students in Training (ANST) Interest Group *Vice President*
2018	**Brain Expo,** Medical College of Wisconsin & University of Wisconsin – Milwaukee Community Outreach Event for Brain Awareness Week *Organizer and Presenter*
2017, 2018	**Eating Disorders Awareness,** University of Wisconsin – Milwaukee & Aloria Health Milwaukee Community Outreach Event for National Eating Disorders Awareness Week *Presenter*
2017	**Go Milwaukee,** University of Wisconsin - Milwaukee Community Outreach Event to promote research accessibility to the public *Presenter*
2017	**National Eating Disorders Association,** Milwaukee, WI *Fundraiser and Walker*
2015 – present	**American Foundation for Suicide Prevention,** Chicago, IL *Fundraiser and Walker*

PROFESSIONAL AFFILIATIONS

- Association for Psychological Science, *Member*, 2018 –
- Hispanic Neuropsychological Society, *Member*, 2018 –
- National Academy of Neuropsychology, *Member*, 2018 –
- Society for Neuroscience, *Member*, 2016 –
- Society for the Neurobiology of Language, *Member*, 2015 –
- Organization for Human Brain Mapping, *Member*, 2013 –
- International Neuropsychological Society, *Member*, 2012 –
- International Association for Women's Mental Health, *Member*, 2011 –

LANGUAGE PROFICIENCIES

- English
- Spanish

ADDITIONAL SKILLS

- E-Prime software proficiency, including E-Studio task building and design for fMRI & MEG implementation
- SPSS, FSL, FreeSurfer, SPM proficiency
- MATLAB, MNE-Python, ANTS, VNC viewer experience
- Unix and Linux shell scripting and python code experience
- Microsoft Word, Excel, Access & PowerPoint, and Adobe Illustrator & Photoshop proficiency