Neural indicators of misophonia related cognitive load

by

Michael A. Tollefsrud

B.A., University of North Carolina at Greensboro, 2018
M.A., North Carolina Central University, 2020

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Psychological Sciences
College of Arts and Sciences

KANSAS STATE UNIVERSITY
Manhattan, Kansas

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Abstract

Misophonia is characterized by disproportionate emotional and physiological responses to specific “trigger” sounds, often accompanied by self-reported difficulty maintaining focus during exposure. This dissertation sought to provide objective evidence of such cognitive disruptions by combining behavioral measures of auditory working memory (WM) with electroencephalographic (EEG) indices of neural processing. Fifty-seven participants (27 misophonic, 30 control) completed a pitch-matching WM task under three distractor conditions: silence, neutral sounds, and individualized trigger sounds. EEG was analyzed using a time–frequency approach to assess changes in alpha (8–12 Hz) and theta (4–7 Hz) oscillatory activity during the retention interval. Behaviorally, misophonic participants exhibited reduced overall WM performance compared to controls and a selective decrease in response precision, without loss of accuracy, when exposed to trigger sounds, suggesting degraded memory fidelity under emotionally salient distraction. From the EEG analysis, misophonic participants showed lower frontal alpha and theta power across conditions, consistent with diminished inhibitory control and reduced cognitive control engagement, rather than trigger-specific effects. These results indicate that misophonia may involve a generalized attentional control vulnerability that amplifies the disruptive impact of emotionally salient auditory stimuli. Implications and directions for future research are discussed.

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Misophonia is characterized by disproportionate emotional and physiological responses to specific "trigger" sounds, often accompanied by self-reported difficulty maintaining focus during exposure. This dissertation sought to provide objective evidence of such cognitive disruptions by combining behavioral measures of auditory working memory (WM) with electroencephalographic (EEG) indices of neural processing. Fifty-seven participants (27 misophonic, 30 control) completed a pitch-matching WM task under three distractor conditions: silence, neutral sounds, and individualized trigger sounds. EEG was analyzed using a time–frequency approach to assess changes in alpha (8–12 Hz) and theta (4–7 Hz) oscillatory activity during the retention interval. Behaviorally, misophonic participants exhibited reduced overall WM performance compared to controls and a selective decrease in response precision, without loss of accuracy, when exposed to trigger sounds, suggesting degraded memory fidelity under emotionally salient distraction. From the EEG analysis, misophonic participants showed lower frontal alpha and theta power across conditions, consistent with diminished inhibitory control and reduced cognitive control engagement, rather than trigger-specific effects. These results indicate that misophonia may involve a generalized attentional control vulnerability that amplifies the disruptive impact of emotionally salient auditory stimuli. Implications and directions for future research are discussed.

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Chapter 1 - A Novel Research Direction for Misophonia

Misophonia is a condition generally characterized by disproportionately aversive emotional and physiological responses to seemingly innocuous sounds (Swedo et al., 2022). These sounds (commonly called a "trigger") can encompass any low-level repetitive noise from any source, including mechanical sounds (ex, keyboard typing, refrigerator humming) or animal noises (ex, bird calls). However, the most common triggers are orofacial sounds (i.e., sounds associated with eating/breathing) generated by humans (Brout et al., 2018). Misophonia symptoms (typically referred to as "responses") can include intense feelings of fear, anxiety, anger, and disgust (Ferrer-Torres & Giménez-Llort, 2022). Prevalence estimates vary, ranging from approximately 3% in the general population (Jastreboff & Jastreboff, 2014) to around 20% in the college population (Taylor, 2017). Physiological assessments (e.g., neuroimaging, heart rate, and galvanic skin response) have found that people with Misophonia (typically referred to as "Misophonic") often experience a fight-or-flight response when exposed to potential triggers (Yilmaz & Hocaoglu, 2021). Additionally, evidence has arisen that trigger exposure can impair Misophonic's cognitive control, resulting in failure to maintain goal-relevant behaviors and suppress goal-irrelevant behaviors. Evidence for this often comes from a self-reported tendency of Misophonics to lose focus on other tasks once they notice a trigger (Daniels et al., 2020).

Such observations highlight an often overlooked but critical component of the misophonic experience: the impact of triggers on ongoing cognitive processing in Misophonics. My dissertation used behavioral measures of working memory performance and electroencephalogram (EEG) measures of sound processing with the goal of providing objective measures of the cognitive interruptions frequently reported by Misophonics. Completion of this project yielded important advances for Misophonia research. Mainly, these are:

(1) A test of the overarching hypothesis that triggers impair ongoing cognitive processing in Misophonics more so than non-Misophonics

(2) An objective behavioral index of cognitive impairment related to Misophonia

(3) An EEG index of response strength to triggers of varying severity

Specific hypotheses related to the methodology employed in this dissertation were as follows.

If Misophonics' ongoing cognition is disrupted more by triggers than non-Misophonics, their working memory performance should be impaired more by trigger sounds than by acoustically similar non-trigger sounds.

Recent evidence suggests that misophonic responses depend less on the spectral characteristics of trigger sounds and more on the individual's identification of and experience with the stimuli. (Kazazis et al., 2024; Samermit et al., 2022; Savard et al., 2022; Siepsiak et al., 2023). Additionally, a core characteristic of misophonia is impaired goal-directed attention when exposed to triggers (Daniels et al., 2020). As such, one would expect greater distraction for misophonia-specific stimuli than for similar non-trigger stimuli. This was assessed by performance on a working memory task, predicting greater disruption in task performance for the misophonic group when exposed to triggers.

If Misophonics have abnormal processing of triggers, their EEG post-trigger presentation should look different from that of non-Misophonics and be specific to trigger-type sounds.

A long-standing assumption for the etiology of misophonia is that there is some abnormality in the processing of triggering stimuli. Support for this idea has been provided by findings of abnormal functional connectivity in specific neurological pathways (Eijsker et al., 2019; Kumar et al., 2017, 2021) and differences in sensory-evoked components between Misophonics and controls (Aryal & Prabhu, 2023; Schröder et al., 2013). Given this evidence for a neurological basis of the misophonic response, I predicted differences in post-trigger EEG responses in Misophonics that are not seen in controls. This project departed from previous EEG responses by using ecologically valid stimuli (trigger sounds) and a time-frequency approach to analyzing the neural responses to misophonic triggers.

There has been little research on how the presentation of trigger sounds yields potentially different neural activities compared to comparable neutral sounds. Due to this, an exploratory approach was employed to analyze post-trigger EEG responses, examining several different features. The hypothesis that brain responses differ when comparing Misophonics to non-misophonics can be potentially characterized by one or multiple EEG features. This is not a weakness at this stage, and reflects a feature independent EEG experiment design (Luck, 2014). Regardless of the particular EEG feature, if differences exist, they will support subjective reports from Misophonics that their issues are related to specific stimuli. Further, future work delving into the specifics of cognitive disruption can take a more focused EEG approach after this initial examination takes place.

Positive Outcomes of the Project

This novel research project on Misophonia promises several significant positive outcomes. First, it provides an objective test of the hypothesis that trigger sounds more severely impair cognitive processing in individuals with Misophonia than in those without the condition, potentially validating the experiences commonly reported by those affected. Secondly, the study evaluated an objective behavioral index to measure cognitive impairment associated with Misophonia, which could be invaluable for diagnosing and assessing the condition's severity. Thirdly, the research assessed an EEG index of response strength to triggers of varying severity, offering a neurological basis for understanding Misophonia. These outcomes advance the scientific understanding of Misophonia and provide tangible tools for researchers to study the condition. Moreover, by using ecologically valid stimuli and a time-frequency approach in EEG analysis, this study offers a more realistic and comprehensive view of how Misophonia affects individuals in real-world scenarios, potentially leading to more effective interventions and support strategies for those affected by the condition.

Chapter 2 - Literature Review

Misophonia History

Research

Misophonia was first described in audiology literature by Jastreboff and colleagues in 2001 while working with patients suffering from tinnitus and what they thought at the time to be hyperacusis. While working with this sample, Jastreboff & Jastreboff noted that some patients had aversive emotional reactions to sounds with specific patterns, regardless of the decibel level or physical characteristics of the sounds. Having determined that the symptoms did not fit the major signs of hyperacusis, Jastreboff & Jastreboff proposed it as a new condition, coining the term "Misophonia" (Jastreboff & Jastreboff, 2023). Since this time, several etiologies for misophonia have been proposed. One of the earliest proposed etiologies was a classical conditioning model where triggers get paired with a period of stress, with the resulting avoidance acting to reinforce this association (Dozier, 2015). In contrast, research employing neuroimaging methods such as fMRI has suggested a neurological basis for the condition. Existing research has observed hyperactivation of the anterior insular cortex (AIC) and the salience network in Misophonics compared to controls; however, further research is needed to confirm the causality of these observations (Kumar et al., 2017; Schröder et al., 2019).

Previous audiological research has suggested that Misophonics are especially bothered by sounds with specific spectral characteristics, as demonstrated by their tendency to be easily triggered by high-frequency sounds (Aazh et al., 2022). This runs counter to the idea that conditioning drives the disorder. Indeed, it has been suggested that the acoustic properties shared by typical misophonia triggers, such as repetitive patterns and temporal modulation, may explain why these sounds become problematic. These features are inherently attention-grabbing (regardless of learning history), increasing the likelihood that they will become the focus of fixation (for review, see Savard et al., 2022). However, growing evidence suggests that responses are driven less by such spectral characteristics and more by the individuals' identification of and experience with the stimuli. Recent research has shown that correctly identifying a trigger ("that is chewing") and the trigger source ("who is chewing?") plays a much larger role in the formation of the misophonic response than any specific acoustic characteristics of sounds (Kazazis et al., 2024; Samermit et al., 2022; Savard et al., 2022; Siepsiak et al., 2023). This stimulus specificity and independence of specific spectral characteristics (e.g., sound intensity) have previously been used to distinguish misophonia from other sound processing disorders such as hyperacusis (Jastreboff & Jastreboff, 2023). That is, Misophonic responses are independent of acoustics and may instead be reliant on extracting semantics from sound. Hyperacusis abnormalities are based solely on the processing of acoustic features.

Common Terms and Concepts in Misophonia Research

Regardless of the theoretical lens used — whether cognitive, psychiatric, or neurological — most research into misophonia employs the same terminology when describing specific aspects of the condition. Common terms relevant to this dissertation are the use of "misophonic" to describe an individual with misophonia, the term "trigger" to describe the stimuli that can induce misophonia symptoms, and "responses" or "misophonic responses" to refer to the symptoms of misophonia in response to trigger exposure (Ferrer-Torres & Giménez-Llort, 2022; Yilmaz & Hocaoglu, 2021). These terms, as described here, will be used throughout this dissertation.

Current Measures of Misophonia and Their Limitations

Several self-report measures have been developed to identify and describe misophonia in the general population. Before discussing these measures, it is worth noting that Misophonia has not yet been given an official diagnostic code in the Diagnostic and Statistical Manual of Mental Disorders (5th ed.; DSM–5) or in the International Classification of Diseases, Tenth Revision (ICD-10). This prevents Misophonia from being "officially" diagnosed. As such, most claims of misophonia status in the context of research have typically relied on scores on self-reports and self-identification with an ever-changing definition of symptoms. Over the last 20 years, numerous diagnostic criteria have been proposed, each emphasizing different aspects of the condition, yet none have achieved consistent, widespread adoption (Dozier et al., 2017; McMahon et al., 2024; Schröder et al., 2013). Likewise, the description of misophonia has been inconsistent, resulting in concerted efforts to standardize it (Swedo et al., 2022), which have been met with mixed reception (Aazh, 2023; Brout, 2022). So, while the measures to be described range in their robustness, none of them should be considered "definitive" measures of misophonia.

A comprehensive review of all major scales/assessments used in misophonia research is beyond the scope of this dissertation (for review, see Ferrer-Torres & Giménez-Llort, 2022). However, a few features are common among most, if not all, of them. Typically, they consist of Likert-like self-reports with items designed to assess the degree to which traditional Misophonic stimuli cause impairments to the respondent's life. Beyond this central thread, scales can vary in terms of scope (ranging from probing specific trigger classes to simply the presence of any trigger) and application (evaluating the presence/severity of symptoms, assessing subjective experiences, thoughts, and appraisals of misophonic situations) (Ferrer-Torres & Giménez-Llort, 2022).

Of note, it has been observed that many misophonia assessments fail to demonstrate sufficient divergent validity to separate it from other similar conditions like hyperacusis. Hyperacusis, like Misophonia, is characterized by intense aversive responses to sounds. However, in hyperacusis, this aversion stems from the loudness of the sound—a physical characteristic—being perceived as intolerable, even at intensities that pose no issues for individuals with normal hearing (Jastreboff & Jastreboff, 2023). While the two conditions emphasize different aspects of sound perception (top-down vs. bottom-up processing), they often co-occur (Aryal & Prabhu, 2023). Some audiological research has even classified misophonia as a subtype of hyperacusis, leading many studies to overlook distinctions between the two (Aazh, 2023).

Additionally, many of the most popular scales have yet to undergo validation studies, which limits the confidence in any conclusions made using these scales (Mednicoff et al., 2022). Furthermore, all these self-reports rely on retrospection. To the author's knowledge, there has yet to be a standardized measure of misophonia intensity/impairment that can be administered online (during trigger exposure/task completion). This is fine when one is interested in simply identifying Misophonia and describing the general intensity of misophonia. However, these measures fall short when one is interested in assessing variation in misophonia intensity in response to different stimuli under varying conditions. Unlike in laboratory settings, trigger exposure in daily life often involves multiple trigger sources and trigger types, both of which can change multiple times throughout an event (e.g., changes in who is eating and what). As such, a method for effectively measuring misophonic responses to changing conditions would have greater ecological validity, while also helping to examine time-related features of the misophonic experience. For example, this could be achieved using behavioral indices of disruption and/or EEG responses to trigger sounds, as was done in this project.

Working Memory and Cognitive Load

Working memory can be broadly defined as the limited capacity to mentally retain and operate on information from the environment for a short period (Salmela et al., 2014). Auditory working memory (AWM) refers to the same concept, but it focuses on processing and operating on auditory information (Kumar et al., 2016). This capacity is illustrated in tasks where participants are presented with a sequence of differing stimuli (for example, pure tones of varying frequency) and then tasked with determining if a final stimulus is the same/different from a specific element in the previously presented array (Joseph et al., 2016). Alternatively, a matching task can be used, in which participants adjust a feature of a response stimulus (e.g., turning a dial to change the pitch of a tone) to match a previously shown target stimulus. The accuracy and precision of these adjustments can be examined, allowing more granular examinations of WMC than simple same/different tasks (Kumar et al., 2013; Tollefsrud et al., 2024; Wisniewski & Tollefsrud, 2023).

In the auditory domain, specifically for non-speech materials, these tasks traditionally consist of having participants identify changes between two sounds separated by a retention interval (Kaiser, 2015). These models assume a fixed capacity ("Slot") model of working memory capacity, where memory is limited to a set number of items of the same level of precision (Joseph et al., 2016; Salmela et al., 2014). Such a model, useful in predicting some outcomes, is limited because it fails to account for the potential variability in memory representations. That is to say, correctly remembering a target stimulus does not mean one has a perfect representation of the target, nor does failing to remember a target preclude any memory representation. Recently, experiments using a matching paradigm have supported a competing interpretation where WM resources can be flexibly allocated to multiple items. In such approaches, participants reproduce the features of interest in the target stimulus, and their performance is based on the accuracy and precision of the matches. This accounts for the continuous nature of memory accuracy, and the success of this model in predicting/explaining experimental outcomes has suggested that WM capacity (WMC) is better conceptualized as a flexible resource as opposed to a slot model (Kumar et al., 2013; Tollefsrud et al., 2024; Wisniewski & Tollefsrud, 2023).

Several factors have been known to impact WMC, including attention (Kumar et al., 2013), duration of retention intervals (Wisniewski & Tollefsrud, 2023), and cognitive load (Plass & Kalyuga, 2019). Of special interest to the current dissertation, cognitive load is traditionally defined as the mental resources needed to complete a cognitive task (Dittrich & Stahl, 2012). However, a more recent and theoretically relevant conceptualization views cognitive load as the intensity of cognitive activity at a given time (Plass & Kalyuga, 2019). This view of cognitive load is especially relevant to working memory as it encapsulates two of its key features: its limited capacity and limited duration. These two features define the limits of working memory, such that one could predict failure for any task whose demands exceed the resources available in working memory or that requires operations that exceed the timescale of working memory. In this view, success on any cognitive task requires the cognitive load of the task to be within the individual's working memory capacity, making cognitive load a relevant factor when considering performance on a working memory task (Plass & Kalyuga, 2019).

In the context of misophonia, this interplay between cognitive load and working memory can explain one of the primary effects of the condition: the inability to focus/reduced task performance in the presence of triggers. The primary symptom of misophonia is an emotional reaction, such as feelings of anger, disgust, or anxiety (Abramovitch et al., 2023; Daniels et al., 2020). Over the past few decades, research has yielded multiple approaches to examining the impact of emotion on cognitive load and memory. One such approach is to view emotion as a source of extraneous cognitive load. This view posits that processing the thoughts and experiences associated with negative emotions competes for the same limited pool of resources as working memory, leading to decreased task performance (Plass & Kalyuga, 2019). Additionally, emotion can directly impact working memory, either expanding or limiting the available resources based on whether the emotion is positive or negative (for a review, see Plass & Kalyuga, 2019).

Additional support for the relevance of cognitive load in the misophonic response is found in research demonstrating the influence of top-down cognitive processes on response formation. A striking example of this can be found in a 2022 study examining the effect of trigger source identification on reported misophonia intensity. Gathering a collection of videos featuring common triggers (eating scenes), the authors edited alternative videos where a non-triggering action (e.g., tearing a piece of paper) was recorded, to plausibly function as the source of a trigger sound. This resulted in two sets of videos: attributable video sources (PAVS), where misophonic triggers were played over non-triggering scenes, and original video sources (OVS), where the triggering audio matched the visual scene. Comparing Misophonic's self-reports of trigger intensity to the OVS videos versus the PAVS videos, the authors found marked reductions in self-reported trigger intensity for the PAVS videos (Samermit et al., 2022).

In another 2022 paper, researchers presented sets of trigger, universally aversive, and neutral sounds mixed with multi-talker babble to varying signal-to-noise ratios (-30, -20, -10, 0, +10 dB). Presentations were followed by options to categorize the sound source, a self-report of the pleasantness of the sounds, and a 15-alternative forced-choice task in which participants had to report the label that best fit the sound they heard. They found that self-reported aversiveness to triggers for the misophonic group increased with SNR and correct responses to the labeling task. This indicated that individuals with misophonia reported sounds to be more unpleasant when they were trigger sounds and when they could correctly identify the sound source (Savard et al., 2022).

In the context of these studies and others like them, it is clear that the correct identification of trigger sources is a crucial component of response formation, implicating top-down cognitive processing. Additionally, research showing misophonia is partially characterized by hypervigilance towards triggers (Murphy et al., 2024) suggests that Misophonics are more inclined to seek out triggers, making them more likely to recognize these triggers and experience negative emotional responses. These emotional responses, in turn, reduce cognitive resources and generate cognitive processes (e.g., rumination) that compete for the same limited resources. This holds significant implications for Misophonics, as the prevalence of typical triggers disproportionately burdens them with an additional cognitive load that would hinder their ability to perform cognitively demanding tasks. Theoretically, this could have a detrimental impact on their quality of life, particularly in work or school settings, and highlights the need for further research into the topic. To date, an empirical assessment with objective measures of trigger-induced disruption has not been conducted.

Cognitive Neuroscience Approaches to Misophonia

To date, few studies have implemented neuroimaging methods to investigate Misophonia, with the majority using fMRI. For instance, In their 2019 study, Eijsker et al. examined response inhibition in misophonia by comparing 25 individuals with misophonia to 25 controls, based on Amsterdam Misophonia Scale scores. Participants completed a stop-signal task during fMRI. Misophonics showed longer stop-signal delays and greater activation in the left dorsolateral prefrontal cortex during response execution. During successful inhibition, they showed increased activation in the posterior cingulate and reduced activation in the frontal gyri relative to inhibition failure. Although general inhibition was not impaired, the findings suggested a response bias favoring accuracy over speed, pointing to underlying perfectionism and compulsivity. Neural activation patterns also indicated greater cognitive control and attentional resource use in the misophonia group (Eijsker et al., 2019).

Another study investigated whether the misophonic response reflects a general aversive reaction or a distinct neurological process. Twenty individuals with misophonia and 22 matched controls rated the annoyance of sounds from three categories: misophonic triggers, generally aversive sounds, and neutral sounds. Although no significant difference emerged between Misophonics' ratings of trigger sounds and controls' ratings of unpleasant sounds, the authors suggested this may reflect differences in how the groups used the rating scale. In the misophonic group, trigger exposure was associated with abnormal functional connectivity between the anterior insular cortex (AIC) and the vmPFC, PMC, hippocampus, and amygdala. Structural analyses further indicated that the misophonic response is driven by AIC hyperactivity and increased connectivity with medial frontal, medial parietal, and temporal regions—supporting the idea that misophonia involves aberrant salience attribution to specific sounds. (Kumar et al., 2017). A similar 2019 study, involving 21 individuals with Misophonia and 25 matched controls, used pre-validated trigger sounds and supported Kumar's 2017 findings. The results showed increased BOLD responses in the right insula, right anterior cingulate cortex (ACC), and right superior temporal cortex in the Misophonia group, indicating that the salience network plays a crucial role in processing trigger sounds in individuals with Misophonia.

These studies revealed valuable information on the potential neurological underpinnings of misophonia. However, the methods used are technically challenging to design protocols for and prohibitively expensive for wide-scale use in misophonia research. A more accessible neuroimaging approach to studying misophonia would be the use of EEG. The earliest example of EEG use in Misophonia research was an examination of dysfunction in the auditory system in individuals with Misophonia (Schröder et al., 2014). They recruited 20 Misophonics, categorized via the diagnostic criteria proposed in their earlier paper (Schröder et al., 2013). They used an oddball task where participants watched a silent movie while exposed to a pseudorandom sequence of standard 1000Hz tones and intermittent deviant tones (higher or lower than the standard tone). The authors recorded participants' EEG during the experiment and examined the P1, N1, and P2 components locked onto the onset of the auditory stimuli. As described by Schröder, these ERPs are all examples of early sensory components evoked by auditory stimuli, including components associated with orienting to new sounds (P1), early attention (N1), and early attention allocation and conscious awareness (P2). From the results of their study, they noted a diminished N1 component to the oddball compared with controls, which they took as suggesting an underlying deficit in the auditory processing system.

Partially consistent results were found in Aryal and Prabhu's (2023) paper that compared the auditory late latency response (ALLR) of Misophonics to that of a control group. The ALLR refers to neural reaction to auditory stimuli processed within/around the auditory cortex, providing insight into the auditory system's functional integrity (Aryal & Prabhu, 2023). In this case, it was assessed using a single-channel system while participants passively listened to a sequence of pure tones. They found a significant difference in peak P1 and N1 latency between the Misophonic and control groups, but not in peak amplitude. These authors agreed with Schröder's conclusions about the presence of deviant cortical-level auditory processing in Misophonics (Aryal & Prabhu, 2023). However, it should be noted that neither study used actual trigger sounds, leaving potentially critical response differences unexamined.

In a departure from other Misophonia EEG work, Ward and colleagues (2022) took a frequency domain approach to examine differences in alpha band power during an auditory aversive generalization task. Auditory generalization learning refers to how operantly conditioned responses are generalized to similar but different stimuli. Ward and colleagues assessed this phenomenon to test the idea that misophonia symptoms result from overgeneralized associative learning of aversive responses. Trained on sequences of pure tones, the results showed heightened sensitivity to aversion generalization in the misophonic group. Additionally, they found a greater reduction in parieto-occipital EEG alpha band power for self-reported Misophonics compared to controls (Ward et al., 2022). Reductions in the alpha band, a rhythm thought to be inhibitory in nature, are typically associated with heightened attentional engagement (Jensen & Mazaheri, 2010). As such, Ward's findings suggest heightened attention to triggering stimuli in Misophonics and possible involvement of enhanced emotional components. Once again, however, no trigger sounds were used.

In Summary, despite the valuable insights provided by the limited number of neuroimaging studies on misophonia, the current research in this field faces several challenges. Most of these studies have relied on fMRI, which, while informative, is technically challenging and costly, limiting its widespread use in misophonia research. EEG, a more accessible alternative, has been employed in a few studies. However, the absence of actual trigger sounds in these experiments raises concerns about ecological validity and the ability to capture the full range of neural responses specific to misophonic triggers. These gaps underscore the need for more comprehensive and methodologically rigorous research that incorporates ecologically valid stimuli to better elucidate the neural dynamics of misophonia.

Chapter 3 - Contrasting Former and Current Approaches

Misophonia is a condition that has a significant negative impact on individuals' quality of life, and the mechanisms underlying it are still being investigated. In support of these efforts, several self-report style measures of misophonia symptoms and intensity have been developed, varying in their focus on specific features and degrees of empirical validity. However, even the most robust measurements of misophonia are limited in experimental applications, as they provide only a single measurement at a single point in time. This limits the applicability of such tools in examining misophonia intensity over changing conditions and hinders the investigation of the time course of the misophonic response.

Some have attempted to circumvent this issue by including multiple periods during which the participant retakes the assessment within an experimental session (Hansen et al., 2021; Siepsiak et al., 2023). However, this is also limited, as many of these measures were not designed for rapid retesting and are difficult to naturally integrate into some experimental designs. Additionally, as Hansen (2021) noted, such self-reports are vulnerable to response biases due to the possibility of a Misophonic describing a sound as more triggering solely because they believe it should be so. Even without considering potential testing effects and response biases, relying on self-reporting creates a bottleneck for the timescale at which the misophonic response can be examined. Specifically, the timescale at which moment-to-moment misophonia experience can be assessed is limited to the time needed to fill out a Likert scale, limiting the temporal fidelity of any description of the misophonic response.

Other methods have been used to address one or more of these problems. For instance, looking at changes in skin conductive response (SCR), heart rate variability (HR) (Siepsiak et al., 2023) and fMRI signals (Eijsker et al., 2019; A. A. Kumar, 2021; S. Kumar et al., 2017) address the issues of testing effects and response bias, and in the case of the first two, have excellent temporal resolution. For instance, a 2023 study found that Misophonics exhibited a deeper deceleration of heart rate (HR) than the control group when listening to congruent human eating sounds accompanied by video stimuli, compared to the control group (Siepsiak et al., 2023). Likewise, previous studies have also shown increased skin conductance responses for Misophonics compared to controls when exposed to trigger sounds (Edelstein et al., 2013).

Lastly, an fMRI study found significantly greater activity in the anterior insular cortex (AIC) in Misophonics when listening to trigger sounds compared to controls, implicating abnormal activity of the salience network in misophonia. It also found hyper-functional connectivity between the AIC and areas involved in emotional processing and regulation (Kumar et al., 2017).

Studies such as these provided great details on the physiological impact and possible underlying neurology of misophonia. However, SCR and HR only provide information on physiological arousal, giving no insights into the cognitive components of misophonia. Additionally, fMRI is notable for its poor temporal resolution, making it unfit for any time-related questions. In contrast, EEG analysis is robust against the issues of response bias and testing effects while also being temporally resolute (Makeig et al., 2004). Additionally, existing research reveals differences in EEG responses between Misophonics and controls, providing a rationale for its utility in exploring misophonia specifically (Aryal & Prabhu, 2023; Schröder et al., 2014; Ward et al., 2022). Likewise, the reported impacts of emotional stimuli, such as Misophonia triggers, on working memory performance via increased cognitive load from such stimuli (Plass & Kalyuga, 2019) make a WM task an ideal behavioral assessment of Misophonia impairment. Examining the overall changes in performance on the matching task based on the presence of triggers could function as a behavioral index of impairment caused by trigger exposure. This can potentially act as converging support for any EEG trends found.

Planned Departure From Existing Misophonia EEG Tasks and Analysis

This dissertation departed from most existing studies by moving away from non-trigger sounds, utilizing time-domain or frequency-domain EEG analysis. Our reasoning for this is twofold and stems from my primary goal of obtaining a reliable indicator of the impairments caused by misophonia triggers over time. First, the existing oddball experiments did not look at how the introduction of misophonia triggers influenced the EEG indices in question; instead, they simply compared the overall ERP differences between Misophonics and controls to non-trigger sounds. While generally informative about the potential underlying processing issues that could be involved in misophonia symptomology, such an approach fails to inform on the impact of triggers themselves. To address these limitations, I piloted two configurations of an oddball task that incorporated triggering versus neutral stimuli, focusing solely on the behavioral results before committing to the inclusion of EEG. The first configuration consisted of a standard oddball task with the periodic inclusion of distractor sounds (triggers or neutral sounds). The second configuration used the same task but had the distractors constantly playing in the background, alternating between triggers and neutral sounds. From this piloting, I found no difference in behavioral performance between Misophonics and controls in trigger vs neutral trials in either configuration. A third configuration replaced the oddball task with the auditory matching task used in my previous work (Tollefsrud et al., 2024; Wisniewski & Tollefsrud, 2023). Overall, I found a general trend toward declining task performance on the trigger trials compared to neutral and silent trials. However, I failed to find a difference between the misophonia and control groups. For more information on these pilots, see Appendix A “Pilot Data”. I believe these results stem from grossly unbalanced samples in each group (9 controls to 30 Misophonics).

Changing The EEG Approach

My second departure from existing misophonia EEG methods, moving past simple ERP analysis, is motivated by the fact that ERP measures remove much information about the dynamics of the neural activity of interest. During any task, the brain undergoes ongoing changes in activity, both related and unrelated to the task of interest. However, the very nature of the ERP as a mean deviation from electrical potential during a given period means you get a single measurement of activity (Makeig et al., 2004). Additionally, the ERP is not calculated on the trial-by-trial level, so it may vary or even be absent in any individual trial used to compute it (Makeig et al., 2004). To address these limitations, this project employed a time-frequency approach to assessing changes in theta and alpha band power in response to trigger exposure. In contrast to ERP, a time-frequency analysis of EEG facilitates examining changes in event-related brain rhythms over time, rather than at a single time point (Makeig et al., 2004).

The alpha rhythm (8–13 Hz), once dismissed as mere cortical “idling” (Pfurtscheller & Lopes Da Silva, 1999), is now widely understood as a functional inhibitory mechanism that suppresses task-irrelevant regions to route processing toward task-relevant networks (Jensen & Mazaheri, 2010). Consistent with this view, multiple studies report a significant enhancement of alpha activity with increased memory load during the retention interval (for review, see Jensen & Mazaheri, 2010), indicating that alpha activity is actively engaged in maintaining information rather than reflecting passive idling (Klimesch, 2012). Alpha power also scales with task difficulty and effortful listening (Wisniewski, 2017), while decreases in the lower alpha range have been linked to general task and attentional demands (Pfurtscheller & Lopes Da Silva, 1999). Clinically, disorders marked by poor distractor suppression (ex, ADHD) may reflect a failure to modulate posterior alpha appropriately, leading to breakdowns in this inhibitory gating process (Jensen & Mazaheri, 2010). Taken together, alpha oscillations appear central to selectively filtering information: they rise to protect fragile working-memory representations and fall when broad engagement with incoming stimuli is required. This makes it a prime candidate for a neural marker of the attentional impairments commonly self-reported in misophonia. Likewise, the frontal midline theta has been shown to be involved in general cognitive control processes and working memory performance, demonstrated by works showing theta enhancement during effortful listening tasks and delayed pitch discrimination tasks (Wisniewski, 2017; Wisniewski et al., 2018).

In summary, departing from previous misophonia research by using a time-frequency approach provided greater information on the changes in misophonia brain states in response to trigger exposure than the traditional ERP approach. Previous EEG research examining alpha and theta rhythms has found evidence of their involvement in cognitive processes such as working memory and sensitivity to task demands, making them excellent candidates for the EEG features for this project. I aimed to provide valuable measures of misophonia impairment that address the limitations of previous EEG research and existing misophonia measurements in general.

Chapter 4 - Methods

Measures

The Duke Misophonia Questionnaire (DMQ) is a psychometrically validated 86-item self-report measure designed to assess misophonia. The DMQ consists of several subscales that can be used independently (Rosenthal et al., 2021). The present study utilized the 12-item Impairment subscale, designed to assess the severity of misophonia-related impairments in daily life. The authors define three severity groups based on scores: minimal to mild (0-13), moderate (14-38), and severe (39-49).

The Hyperacusis Questionnaire (HQ) is a 14-item self-report designed to assess the presence and severity of hyperacusis, or the tendency to report discomfort for sounds at intensities that most normally hearing people find acceptable (Khalfa et al., 2002). The original cutoff score was any score greater than 28; however, a recent reanalysis incorporating uncomfortable listening levels concluded that scores of 22 or higher are consistent with clinical hyperacusis (Aazh & Moore, 2017). This cutoff was used in this project. The HQ was selected to screen for hyperacusis as it has been previously shown to be capable of at least partially separating misophonia from Hyperacusis (Smees et al., 2024).

The Self-Assessment Manikin (SAM) is a visual tool to assess emotional responses to stimuli. The tool consists of three sequences of humanoid pictures that act as non-verbal indicators of subjective feelings of pleasure (positive/negative), arousal (minimal/intense), and dominance (feeling in control/out of control) (Bradley & Lang, 1994). This tool has been a staple in emotional research since its inception in 1980 and continues to see use in clinical and research settings (Adalarasu, 2017). This study employed a digital version of the newer nine-point scale (Yang et al., 2018) to obtain individualized rankings for the valence and arousal produced by all potential distractors. These individualized rankings were used to validate the classification of stimuli as either triggering or neutral.

Participants

Participants were recruited from the Kansas State University undergraduate population and the general Manhattan, Kansas, area, and received a combination of course credit and/or $45 for their participation. Recruitment occurred in two phases; the first phase involved hosting a brief survey on Sona, which included the Duke Misophonia Questionnaire, the hyperacusis Questionnaire, and a demographics probe. Respondents were later contacted to offer participation in the full study for a greater amount of research credits if they scored below a 22 on the hyperacusis questionnaire to ensure that recruited participants do not have comorbid sound sensitivities unrelated to misophonia. Additionally, participants were only contacted if they indicated that they were at least 18 years old and had normal hearing.

Participants were categorized into the misophonia/control groups based on scores on the impairment subscale of the Duke Misophonia Questionnaire, with those scoring <14 (the cutoff for moderate severity) classified as controls and those scoring 14 and higher classified as Misophonics. This cutoff score was selected to ensure that participants analyzed as part of the misophonia group exhibit at least moderate impairment, while still allowing for a decent variability in the intensity of symptoms among the misophonic participants, as opposed to biasing the sample by only selecting the end of the scale.

From the respondents to the survey, a total of 88 participants were recruited and processed through both days of the study. An initial target of 60 people, 30 per group, was selected through a power analysis, assuming an effect size of Cohen's d = 0.5 for the critical within-subject comparison of trigger sound versus neutral sound. The power analysis showed that I needed 27 subjects per group to achieve 80% power. I rounded my initial target up to 30 per group to account for inevitable issues with data quality that may arise during EEG data collection (e.g., excessive participant movement). After accounting for participants' data that was dropped due to technical issues or insurmountable EEG noise, I ended up with 30 controls and 27 misophonics, for a total N of 57, which is well within the initial power analysis estimate.

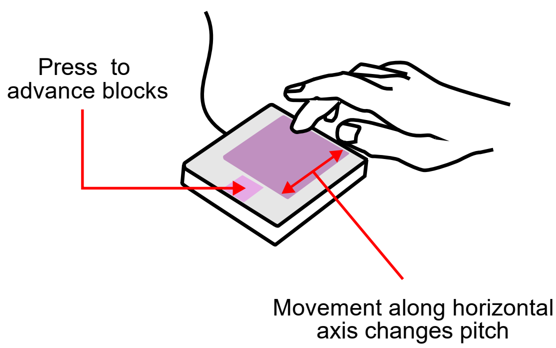
Equipment and Materials

Electroencephalography (EEG) was recorded using a BioSemi Active II system (BioSemi, Amsterdam, Netherlands) operated at a sampling rate of 2048 Hz and an A/D resolution of 24 bits. A 70-channel electrode array was used, comprising a cap with 64 electrodes positioned according to the international 10-20 system, which was fitted to each participant's head. The remaining six electrodes were placed below each eye, lateral to each eye, and on each mastoid. The signals were referenced online to the Common-mode-sense/driven-right-leg (CMS/DRL) reference specific to the Biosemi system (detailed information available at biosemi.com). To ensure data quality, DC offsets between CMS/DRL and each electrode were maintained below 25 µV; any electrode exceeding this threshold was excluded from analysis.

During all sessions, participants sat in a sound-attenuating booth (WhisperRoom, Knoxville, TN). During day 1, all auditory stimuli were presented over Sennheiser HD-280 closed-back headphones connected to an RME UC audio interface (RME Audio, Germany). On day 2, auditory stimuli were played over two Reftone LD-3 stereo speakers (RefTone, Woodland Hills, California) connected to the same device. On both days, sounds were presented at a comfortable listening level not exceeding 80 dB SPL. Participants moved their finger along a pressure-sensitive Roli Lightpad Block MIDI controller to enter responses (see Figure 1). The pad was set up so that movement along the horizontal axis could change the pitch of a sound from low to high. This was used for the pitch-matching task, which assessed working memory performance (see below).

Figure 1.

Matching Response pad



Note. This is the same device used in my previous studies. Adjustments to response tones were made by moving one finger along the x-axis of the purple square. A pink square was used to advance through instructions. Image modified from Tollefsrud et al. (2024).

Stimuli

Target sounds for the working memory task consisted of 1-second pure tones ranging in frequency from 200 to 800 Hz. Stimuli were presented at a comfortable listening level <= 80 dB SPL. The starting value of the response tone depended on where the participant first touched the pad on each trial. Targets were randomly sampled logarithmically along the range of possible values. Distractor sounds consisted of sound clips 3.5 seconds long, including a 10-millisecond on/off ramp.

Consistent with previous research, distracting sound clips consisted of various environmental and human-made sounds sourced from online repositories (Hansen et al., 2021; Samermit et al., 2022). Additionally, to ensure that the trigger sounds produce the maximal effects, all stimuli were edited to be maximally identifiable (i.e., so that people can guess what the sound is) (Savard et al., 2022). Distractors were grouped as "triggers" and "neutral" based on whether they were misophonia triggers, as verified by individual rankings obtained in the distractor evaluation task on day 1. Distractors were played based on the block type. With a random trigger pulled from the trigger bank on trigger blocks, neutral segments pulled during neutral blocks, and no sound playing during silent blocks. Details of each sound clip, including length, description, and original source, are available in the supplemental material. A list of the general source sounds and descriptions is provided in Table 1.

Table 1.

Sound Bank ID's and Descriptions

Source ID	Type	Description
N2	Neutral	A kitchen timer in bathroom. There are a few faint drips from a leaky faucet
N5	Neutral	footsteps on concrete
N6	Neutral	Ambiance of the City at night
N7	Neutral	recording of silence in an open concert hall - includes some static and faint human noises.
N8	Neutral	birds chirping in the countryside
N9	Neutral	ambient forest sounds
N12	Neutral	city playground
N13	Neutral	Water Beach Ocean Waves Constant Splashing Rocks Many Small Waves
N14	Neutral	A distant low rumbling thunder. Rain falling against my room's walls and windows, and some more direct raindrops falling into the open window.

Source ID	Type	Description
N16	Neutral	Sweeping chips near the machine with a broom.
T1	Trigger	actor sips empty drink through straw
T2	Trigger	actor eats a cheese crisp
T3	Trigger	sniffing
T5	Trigger	actor eats almond butter
T6	Trigger	Sounds of eating cereal
T7	Trigger	Eating soup, with bread and a salad
T8	Trigger	Loudly eating a watermelon.
T13	Trigger	eating carrots

Note. Table holding the generic names of the source sound files used, along with the stimulus type it was assigned and a brief description. These sources were segmented into 3.5-second clips to produce the final set of 30 triggers and 30 neutral stimuli. Segmentation was performed to maximize the identifiability of the sound source. Detailed information on the source sounds and segmentations made can be found in the supplemental document "segmented stim bank Info"

Procedures

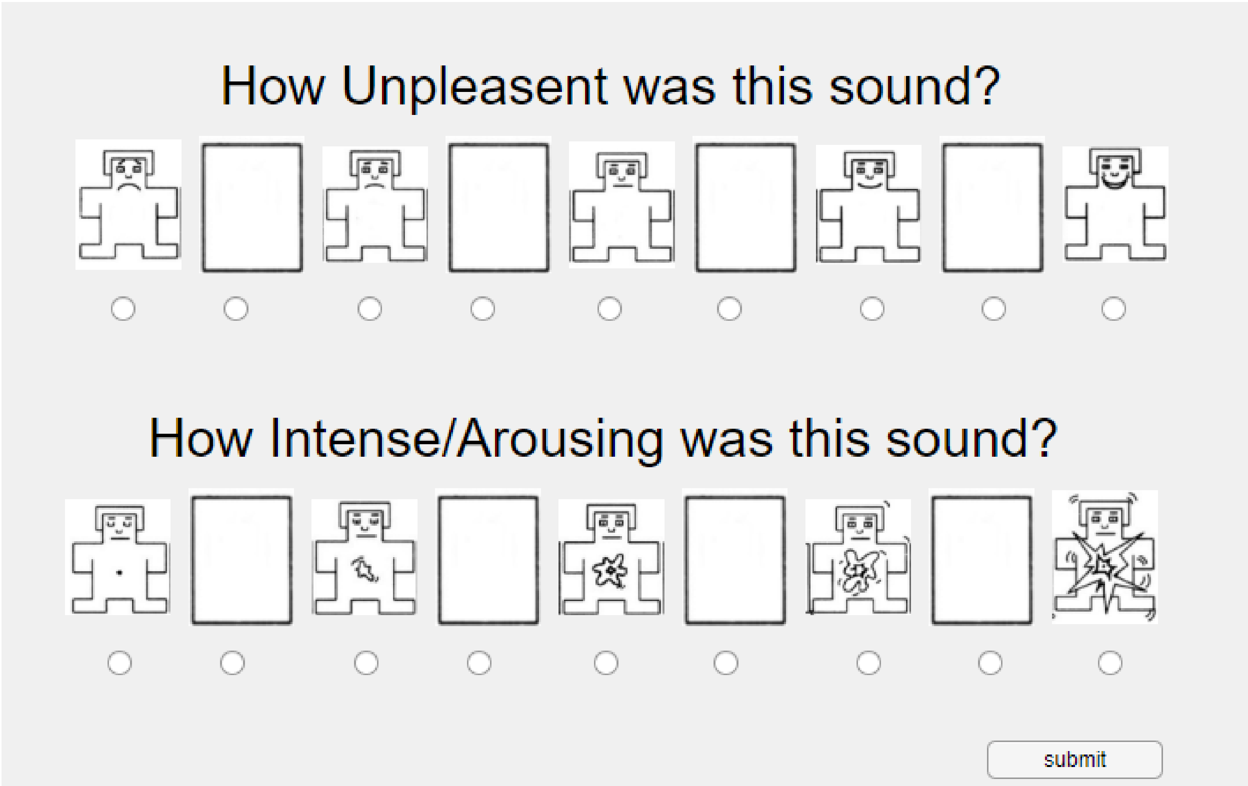
Day 1 Procedures

Distractor Evaluation Task

After giving informed consent and being seated at a table inside the sound booth, participants underwent a task in which they ranked a series of potential stimuli based on valence (positive/negative) and arousal (mild/intense). To this end, participants sat in the booth with headphones on and were shown each potential interfering stimulus individually. After each presentation, they were given the SAM to gauge their affective response to the stimulus (see Figure 2). These individualized rankings were used on day two when assigning stimuli to the trigger and neutral categories. Specifically, the five trigger sounds that scored lowest in valence and highest in arousal were presented to the participant as triggers. This was to ensure that trigger sounds were perceived as sufficiently aversive and intense to maximize the likelihood of producing the expected effects, if they exist. Likewise, neutral sounds were only presented if they had a valence of 5 and an arousal of ≤ 5, ensuring the sounds were neutral and avoiding overly arousing stimuli that could confound the results. Out of the full bank of 30 sounds per type, the 5 that best fit the score cut-offs for each group were assigned as the individualized sets of distractors.

Figure 2.

SAM Screen



Note. The figure depicts the screen participants saw when using the Self-Assessment Manikin to rank distractor stimuli on their valence and arousal (Bradley & Lang, 1994). The screen depicts humanoid figures illustrating various levels of valence (negative on the left and positive on the right) and arousal (calm on the left and aroused on the right). This study employed the more modern 9-point version of the scale, enabling more nuanced responses.

Pitch Matching Task

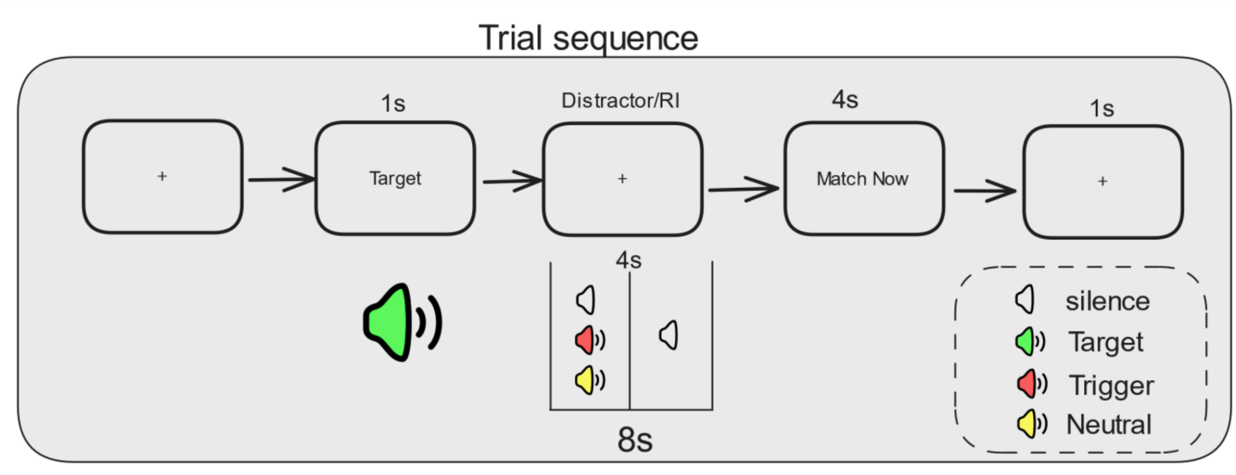
Returning to the booth, participants completed a training block to familiarize themselves with the pitch-matching task to be performed on day 2. The training block consisted of 10 trials. Each trial began with text on the screen saying "Target," and the target sound played over speakers in the booth. This was followed by an 8-second silent retention interval (RI). Following the RI, the text "match now" was displayed, prompting participants to use the touchpad to produce a sound with a pitch that matched their memory of the target. Participants had four seconds after being prompted to make their match, after which their current response was recorded, and the trial ended. At the end of the block, a screen displaying participants' performance was shown to provide feedback on their task completion, and the experimenter then prepared them for the next task. This training was repeated until the participant displayed an overall median response error of < 3 semitones. After completing the task training, participants were scheduled for the day 2 session.

Day 2 Procedures

On day 2, participants were informed about the major differences between training and testing. This included the addition of periodic distractor sounds inside the retention interval. Distractors were played during the first 4 seconds of RI, with the last 4 seconds being silent. The reasoning behind this two-step retention interval is that introducing anything during the retention interval adds variability to theta band activity, making interpretation difficult. Ensuring that there is a fully silent aspect to the Retention interval means there is time for auditory-induced theta changes to resolve, allowing us to examine theta in relation to working memory maintenance. Our previous works have shown that participants maintain sufficient accuracy on this task for retention intervals up to 8 seconds long (Wisniewski & Tollefsrud, 2023), so we set the RI to 8 seconds divided evenly among the interference and silent portions to allow for the maximal duration of interfering stimuli (and thus the largest possible effect) as well a good amount of time to look at post distractor brain responses.

Participants completed 15 blocks, each with 15 trials, resulting in an even distribution of trigger, neutral, and silent blocks. The order of block type was randomly set across participants. This trial procedure is visualized in Figure 2. Once it was confirmed that the participants were ready to continue, they were set up with the EEG cap as described previously, reminded that they could end the session at any time without penalty, and run through the procedures described. To help counter any emotional distress caused by exposure to misophonia triggers 2 minutes of soothing silent videos were played at the end of the final block. The Auditory Learning and Cognition lab had a bank of such videos that we had used in previous research to stave off fatigue, and they acted equally well to ensure the participant left the session in an okay emotional state. Participants were also informed of the counseling services offered at K-State should they require them. Sessions concluded with a debrief.

Figure 3.
Trial Sequence



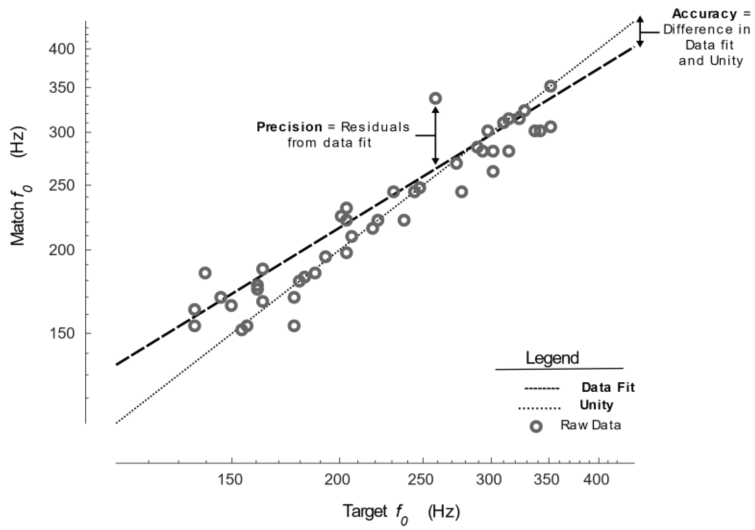
Note. Figure Illustrates the sequence of events in each trial. Each square illustrates the visuals on screen, with the speakers' colors coded by the accompanying sounds. Note that only one sound type is played in the first half of the distractor/RI section per trial, and that no distractors are played during the training session on day 1.

Analysis

WM Performance Analysis

Separate accuracy and precision measurements were extracted from the matching data, following the same approach as in previous works (Tollefsrud et al., 2024; Wisniewski & Tollefsrud, 2023). This involved fitting individual linear regressions for each participant in each distractor condition, predicting participant responses as a function of the target value (see Figure 2 for an illustration). These accuracy and precision values were evaluated using linear mixed-effects models, fitted with maximum likelihood via MATLAB's Statistics Toolbox. Accuracy and precision were evaluated using separate models, with distractor type as a categorical fixed effect (reference-coded to the "neutral" condition). Participant group (misophonic vs. control) based on DMQ cutoff scores was set as a categorical fixed effect. Additionally, the interaction between the distractor type and the participant group was included as a fixed effect, and individual participant intercepts and slopes were treated as random effects. These full models were compared to models with the fixed effects removed. Comparison was made via likelihood ratio tests, with the X^2 degrees of freedom consisting of the difference in number of coefficients between the models being compared.

Figure 4.
Example WM Accuracy and Precision Measurements



Note. Example matching data from a single participant from a past study. The unity line represents where perfect responses would fall; data fit represents the responses based on the individual regression. The dots represent responses on individual trials (Tollefsrud et al., 2024).

EEG Analysis

EEG data was down-sampled to 256Hz, band-pass filtered between 0.5 and 100 Hz, and re-referenced with an average reference. After rejecting data contaminated with excessive noise or movement artifacts through visual inspection, the data were submitted to independent component analysis. Components were then labeled using the "ICLabel classifier" plugin EEGLAB. The plugin automatically assigns source labels to components (e.g., eye, brain, heart, etc.) along with a confidence rating (Pion-Tonachini et al., 2019). Examining the first 20 components, all components labeled as "eye" with a confidence level of≥ 80% were marked for rejection as eye movement artifacts, with no more than six components removed from any individual participant. Following data cleaning, missing channels were interpolated using spherical interpolation.

Epochs were extracted from -3 to 8 seconds surrounding the onset of the retention interval. Event-Related Spectral Perturbations (ERSPs) were computed using complex Morlet wavelets (3 Hz to 10 cycles at the highest frequency of 50 Hz) to obtain time-frequency representations. Baseline correction was applied using the mean power in a pre-stimulus period (-3 s to -1s) and converting relative power to decibels. ERSPs were first inspected by averaging across all channels and plotting scalp maps for features showing clear relative power changes from baseline. Given that there has been very little work with this methodology, the data-driven approach allowed an analysis of actual event-related dynamics. As will be clearer in the results chapter, a focus on arbitrary time-frequency windows (e.g., theta during retention) could lead to analysis of data features unaffected by task events.

Predicted Results

Predicted WM Performance

We predicted that the distractor type would significantly affect the accuracy of responses for the misophonic group. Specifically, I predicted significantly worse accuracy for Misophonics on the trigger trials than on both the neutral and silent trials. For the control group, I predicted significantly worse accuracy for the trigger and neutral trials compared to the silent trials, indicating a general distraction effect, but no significant difference between the trigger and neutral trials. I predicted worse performance for the neutral trials than the silent trials for all participants. Confirmation of these predictions would support our hypothesis that Misophonics' ongoing cognition is disrupted by triggers more so than non-Misophonics and demonstrate that this trigger-specific disruption is more than simply the result of introducing a distractor into the retention interval.

To address potential concerns about individual differences in working memory, it is important to note that any relationship between working memory skill and our measure should be consistent across all conditions. Furthermore, to the best of our knowledge, there is no evidence suggesting that Misophonics have inferior overall working memory abilities compared to non-Misophonics. Therefore, we anticipate that any observed differences in group performance will be attributable to our experimental manipulation.

Predicted EEG Outcomes

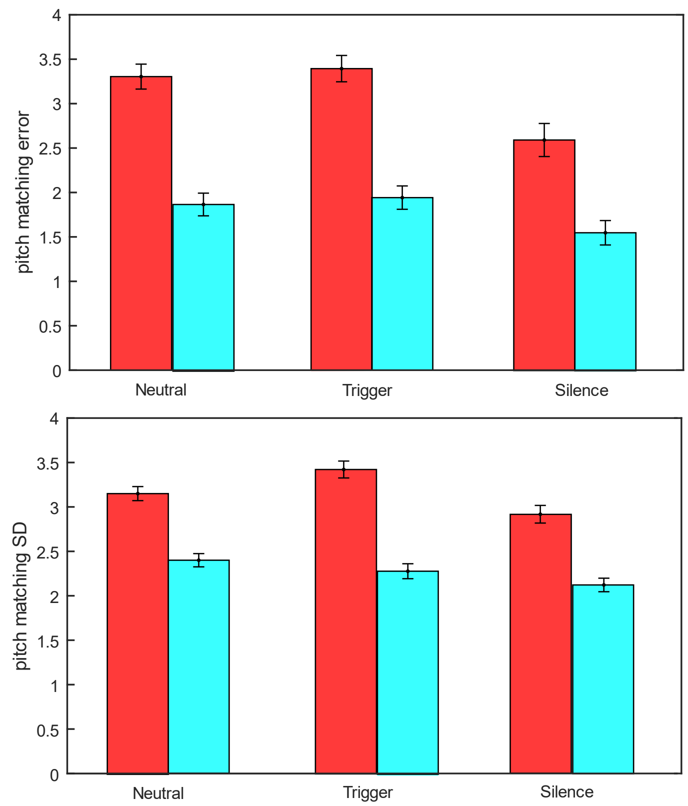
An important note about my EEG predictions is that although I had reason to make predictions on the specific frequency bands discussed below, the exact frequency band where any such effect is found is not the primary point of the study. The overarching prediction was that there would be systemically different event-related responses to trigger trials for the misophonia group, and that this enhanced response would not be observed in the control group. So, while I had general ideas about where such differences would be (as described below), an exploratory analysis of the data beyond that described here was informative and, arguably, necessary given the novelty of the questions being posed and methods being used.

For both groups, I predicted stronger event-related responses during distractions. Specifically, increased alpha activity during the retention interval acts to inhibit task-irrelevant processes during memory maintenance, and this enhancement would be stronger for the neutral and trigger trials compared to the silent trials. Additionally, for both groups, I predicted an increase in theta activity during the retention interval of silent trials, acting to support the maintenance of the target memory. Beyond these general outcomes, I predicted significant interactions between the effects of misophonia status and distractor condition, indicating misophonia-specific effects. Specifically, I predicted that my assumed post-target alpha and theta enhancements would be significantly larger for the misophonic group during trigger trials than neutral trials. Confirmation of these results would support the idea that misophonia triggers are processed abnormally in individuals with misophonia, but not in those without it.

Chapter 5 - Results

WM Task Results

Figure 5.
WM Results



Note. Target matching accuracy (top) and matching precision (bottom) based on trial type for Misophonics (red bars) and Controls (blue bars). Results are shown in semitones. Error bars show within-subject standard errors of the mean (Cousineau, 2005).

Figure 5 shows the mean accuracy (top) and precision (bottom) data for both the misophonic group (red) and the control group (blue) by the type of interference given during the first half of the retention interval. To examine the effects of interference type and misophonia status on task performance, we fit a series of linear mixed-effects models using maximum likelihood estimation in MATLAB’s Statistics and Machine Learning Toolbox. Separate models were fit for each outcome variable (accuracy and precision), with fixed effects of condition, group (referenced to the control group), and their interaction to assess whether the impact of interference type varied by group. Random intercepts and fixed slopes were included for each participant for the within-participant factor. To interpret specific contrasts (e.g., group differences within a given condition), we re-referenced the categorical condition variable so that the group coefficient reflected differences between misophonic and control participants within the reference condition. To assess overall group differences across all conditions, we also fit models excluding the interaction term and compared them to the full models using likelihood ratio tests, with the difference in the number of parameters used as the degrees of freedom for the χ^2 statistic.

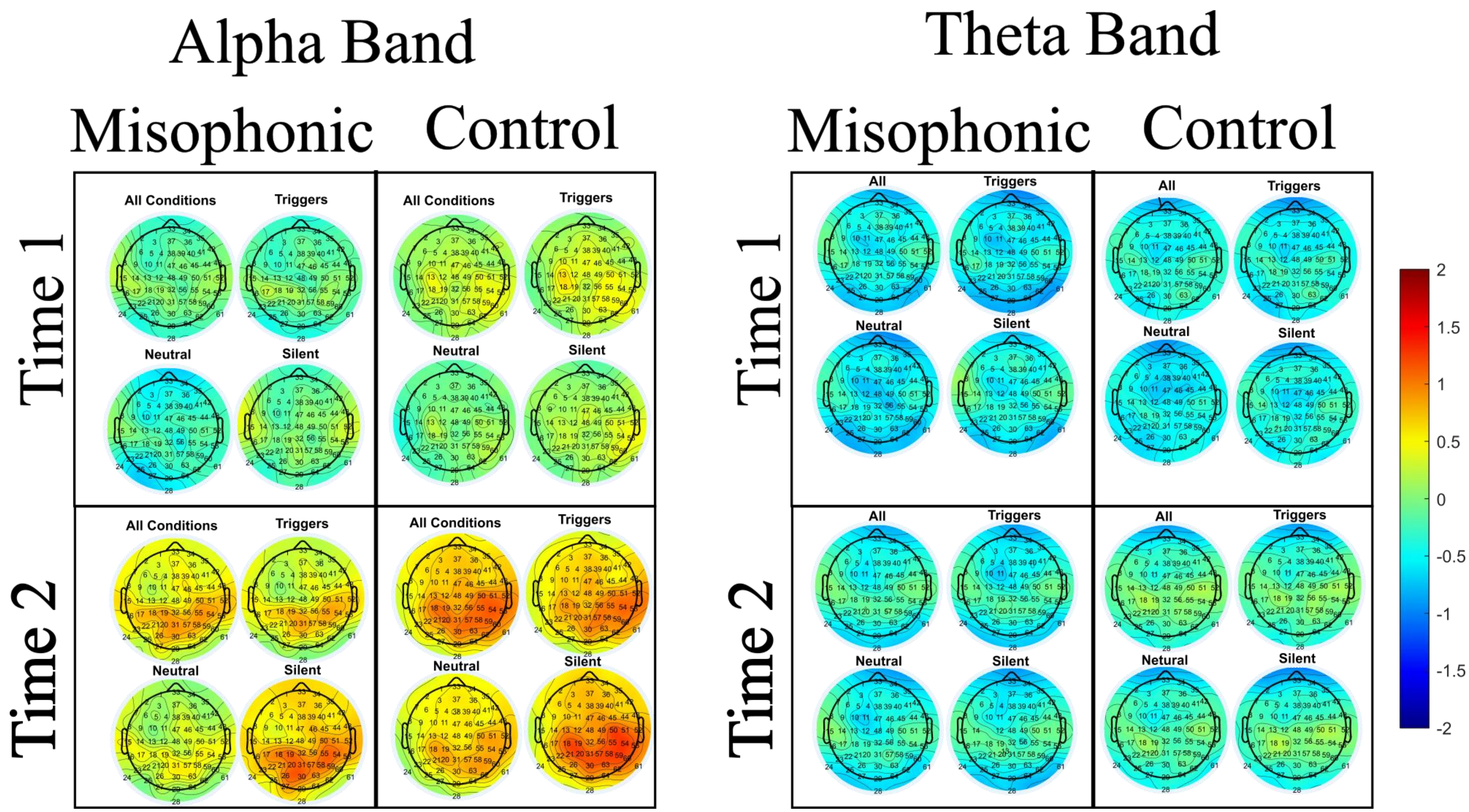
For the accuracy of target matches, a likelihood ratio test showed non-significant effect of interference type on accuracy, $\chi^2(2) = 5.67$, $p = .06$, but there was a significant main effect of group, $\chi^2(1) = 6.73$, $p = .01$. Additionally, the anticipated interaction between misophonia status and trial type (trigger vs. neutral) was not significant, $\beta_{trig:misophonic} = 0.07$, $t(165) = 0.24$, $p = .81$, providing no evidence for selective impairment of accuracy in the misophonia group when comparing trigger to neutral trials. However, in a model excluding the group × condition interaction, misophonic participants performed significantly worse than controls across all conditions, $\beta_{Misophonic} = 1.05$, $t(167) = 2.29$, $p = .02$, suggesting a general performance impairment associated with misophonia.

Precision of target matches showed similar trends, with a likelihood ratio test revealing a significant effect of interference type on precision, $\chi^2\ (2) = 8.24$, $p = .02$, and an overall effect of group, $\chi^2(1) = 4.26$, $p = .04$. Notably, a targeted comparison between trigger and neutral trials revealed that misophonic participants performed significantly worse in the trigger condition, $\beta_{trig:misophonic} = 0.42$, $t(165) = 2.18$, $p = .03$, supporting a selective impact of trigger exposure on performance in the misophonic group. Additionally, as with overall task accuracy, the Misophonic group had overall worse precision in responding across all conditions, $\beta_{Miisophonic} = 1.06$, $t(167) = 2.29$, $p = .02$.

EEG Results

Figure 6.

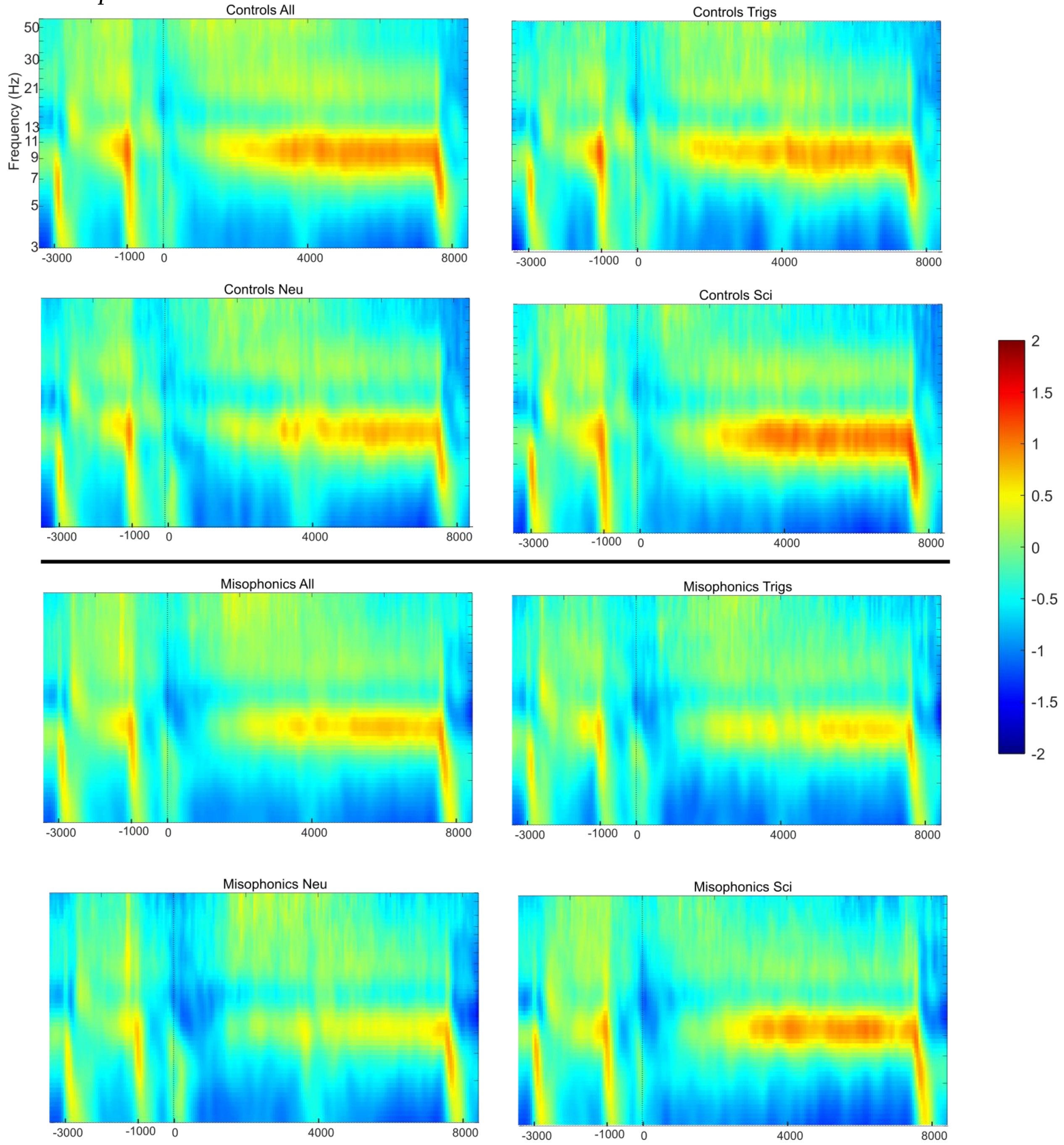
Alpha and Theta band Scalp Maps



Note. Scalp maps showing alpha band and theta band power per group per trial condition. Time 1 indicates the average power from time 0:3500, corresponding to the period where distractors (if present) were played. Time 2 corresponds to time 4000:8000, corresponding to the part of the retention interval that was always silent

Figure 7.

ERSP Per Group Per Condition



Note. ERSP plots for each group divided by trial condition. X-axis is labeled to show times of interest in milliseconds. -3000 = start of baseline, - 1000 = end of baseline and presentation of target tone. 0 = start of interfering phase of retention interval, 4000 = start of the always silent part of the retention interval 8000 = end of RI, beginning of task responding

To examine condition- and group-related changes in neural activity, we analyzed ERSP-derived changes in oscillatory power for the alpha (8–12 Hz) and theta (4–7 Hz) frequency bands. Following the approach used for behavioral data, we fit a series of linear mixed-effects models using maximum likelihood estimation in MATLAB's Statistics and Machine Learning Toolbox. Separate models were constructed for each frequency band, with mean power as the dependent variable. Each model included fixed effects of trial condition, time (RI1 vs. RI2), and group (referenced to the control group), along with their interactions, to assess whether the neural impact of interference varied across time and group. Importantly, Time 1 corresponded to the portion of the retention interval during which interfering sounds (if present) were played, while Time 2 captured a silent period common to all conditions, allowing us to isolate sustained neural effects of interference beyond stimulus presentation. To assess topographic differences in group effects, we included electrode site (Fz vs. Pz) as a categorical fixed effect and modeled its interaction with group. Random intercepts and random slopes for time, condition, and their interactions with group were included for each participant to account for individual variability in power dynamics. Rather than averaging across channels, we selected two representative electrode sites (Fz and Pz) based on topographic distributions of alpha activity (Figure 6) to preserve regional specificity while limiting model complexity.

For the mean Alpha activity, likelihood ratio tests showed a nonsignificant group effect, χ^2 (1) = 0.23, p = .63, but significant effects of trial type, χ^2 (2) = 6.18, p = .05, time, χ^2 (1) = 13.70, p < .001, and electrode site, χ^2 (1) = 5.73, p = .02. Alpha power was significantly greater during RI2 compared to RI1, β_{RI2} = 0.44, t(670) = 2.55, p = .01, overall, and was significantly lower in the Neutral condition compared to the Trigger condition across the sample, $\beta_{trialType\_Neutral}$ = -0.36, t(670) = -2.54, p = .01. A significant time × trialType interaction indicated that Silent trials showed greater alpha power at RI2 compared to Trigger trials, $\beta_{time2:silent}$ = 0.36, t(670) = 2.57, p = .01. A main effect of electrode site revealed lower alpha power at Fz compared to Pz, β_{Fz} = -0.13, t(670) = -2.40, p = .02. Lastly, a significant interaction between electrode and group indicated that misophonic participants exhibited lower alpha power at Fz compared to controls, $\beta_{Fz:Misophonic}$ = -0.19, t(670) = -2.46, p = .01.

For theta, likelihood ratio tests showed nonsignificant effects of group, χ^2 (1) = 0.001, p = .97, trial type χ^2 (2) = 3.34, p = .19, and time, χ^2 (1) = 4.38, p = .04, but a significant effect of elecrode site, χ^2 (1) = 14.92, p < .001. Theta power was significantly lower at Fz compared to Pz,

β_{Pz} = -0.19, $t(670) = -3.91$, $p < .001$. A significant interaction between electrode site and group was observed, indicating significantly reduced theta power for FZ in misophonic participants compared to controls, $\beta_{Pz:Misophonic}$ = 0.14, $t(670) = 1.97$, $p = .050$.

Chapter 6 - Discussion

Recapping background, methods, and predictions

Exposure to trigger sounds for misophonia, a condition characterized by extremely negative responses to specific sounds, has long been proposed to have an impact on the cognitive function of those with the condition. Support for this impact has, until now, relied primarily on anecdotal evidence and self-reports, with no meaningful attempts made to objectively measure this impairment. This dissertation aimed to experimentally test whether misophonic trigger sounds disrupt cognitive processing in individuals with misophonia and whether this disruption can be objectively measured using behavioral and EEG indices. To do so, 57 participants were screened using the Duke Misophonia Questionnaire, resulting in 27 individuals classified as misophonic and 30 as controls. Each participant then provided individualized arousal and valence ratings for a bank of sounds, which were used to classify stimuli as personally aversive (i.e., misophonic triggers) or neutral. Following this, participants were trained on a pitch-matching working memory task where they were presented with a target pure tone followed by a silent retention interval. After the retention interval, participants adjusted the pitch of a response tone to match the target tone. They then completed the full task while EEG data were recorded using a 64-channel cap, with the retention interval filled with either silence, neutral sounds, or misophonic trigger sounds. The outcomes of interest were the accuracy and precision of the participants' matching attempts. The primary behavioral prediction was that individuals with misophonia would exhibit greater impairment in working memory performance and altered neural responses when exposed to misophonic triggers, compared to both neutral sounds and responses from control participants. These predictions were partially supported, as described below.

Behavioral findings, conclusions, implications

The behavioral findings indicate that while triggers did not significantly impair overall accuracy of responses, there were significant effects of distractor condition and group on response precision, with an interaction suggesting greater disruption for Misophonics, specifically in response to trigger sounds. In the context of continuous response tasks, such as those in this project, the measures of accuracy (mean absolute error of response from the target in semitones) and precision (standard deviation of the errors) of task responses reveal different aspects of memory. Changes in accuracy reflect a systematic shift in the memory representation of the target item, evident in this case by a consistent shift up or down in pitch. In contrast, changes in precision indicate changes in the fidelity of those representations. For example, in my earlier work I used a similar pitch-matching paradigm where the target sound was a multitone complex and the interfering sounds were either other tone complexes or white noise (Tollefsrud et al., 2024). In that study, the multi-tone distractors impaired both accuracy and precision, suggesting a disruption to the memory content itself, while white noise increased only precision errors, indicating added noise without altering the core pitch trace.

In the current study, distractors reduced precision but did not impair accuracy, likely because their spectral characteristics differed from those of the target. Some distractors, such as gum chewing, lacked clear fundamental frequency content, minimizing direct systematic distortion of pitch traces. Notably, the misophonic group showed a significantly greater loss in precision under the trigger condition compared to controls. This suggests that trigger sounds introduce additional strain and noise into working memory representations, disrupting fidelity without causing complete forgetting. This selective reduction in precision among misophonic individuals suggests that triggers disrupt the executive attention required to maintain stable memory traces, leading to reduced fidelity. This suggests that misophonic triggers may not always lead to overt errors but can make cognitive tasks more effortful or less efficient. This aligns with working memory theories that emphasize attention's role in shielding representations from interference (Oberauer, 2019) and mirrors self-reports from misophonics who report that exposure to triggers impairs concentration (Edelstein et al., 2013; Johnson et al., 2013).

Attention, though a broad and variably defined concept, is widely regarded as central to many models of working memory (WM). It is often conceptualized as a selection mechanism that enables WM by facilitating selective information processing. This includes filtering out irrelevant stimuli, removing outdated representations, and focusing on specific items within WM (see Oberauer, 2019, for review). Cognitive load theory further suggests that emotionally salient stimuli impose extraneous cognitive load, consuming limited cognitive resources and impairing memory (Plass & Kalyuga, 2019). Disruption of selective attention by emotionally charged but task-irrelevant stimuli can therefore degrade WM representations and reduce overall cognitive processing capacity. In misophonia, this is reflected in the frequently reported tendency to hyperfocus on trigger sources, often at the expense of ongoing cognitive tasks (Edelstein et al., 2013; Johnson et al., 2013).

EEG findings, conclusions, implications

Focusing our analysis on electrodes corresponding to Fz and Pz, several key findings emerged. First, we did not find the anticipated interaction between misophonia and trial type for either alpha or theta activity. Although alpha power was significantly greater during Trigger compared to Neutral trials across the full sample, the absence of a group-specific effect suggests that this response reflected the generally aversive nature of the sounds, rather than a misophonia-specific reaction. In contrast, we observed significantly reduced alpha power at Fz in the misophonia group during distractor presentation (Time 1), regardless of condition, which mirrors the results from the only other existing study that examined alpha activity in misophonia (Ward et al., 2022). Under the alpha-as-inhibition framework, this pattern suggests a general impairment in the ability to suppress distracting input. This interpretation is consistent with the behavioral data, which showed that misophonic participants performed worse overall than controls, independent of trial type. Supporting this further, the misophonia group also exhibited reduced theta power at Fz during Time 1 across all conditions. Given that frontal theta is typically enhanced during effortful listening and delayed pitch discrimination tasks (Wisniewski, 2017; Wisniewski et al., 2018), this reduction may indicate decreased engagement of cognitive control processes involved in WM maintenance.

The findings from both behavioral and EEG measures indicate that individuals with misophonia show measurable differences in how they process distracting sounds. While some of these effects were not specific to misophonic trigger stimuli, the overall pattern suggests heightened distractibility and reduced neural attentional control mechanisms in misophonia. The concept of general attentional deficits in misophonia is supported by several lines of evidence, one of which is its common comorbidity with attention-deficit/hyperactivity disorder (ADHD), a condition characterized by disrupted attentional control (Rouw & Erfanian, 2018). Previous research has also demonstrated attentional differences in individuals with misophonia. For example, a 2023 neuropsychological study incorporating comprehensive cognitive assessments and self-report measures found a significant correlation between misophonia severity and a measure of sustained attention, suggesting that attentional control difficulties may play a role in the condition (Abramovitch et al., 2023). Similarly, a study using a dichotic listening task with chewing sounds reported that misophonic participants had a lower percentage of correct responses than controls, indicating selective attention impairments in misophonia (Silva & Sanchez, 2019).

Taken together, these converging lines of evidence suggest that attentional control deficits may represent a core feature of misophonia, contributing to both its cognitive and emotional impact. Such deficits are not unique to misophonia; they are also observed in conditions like ADHD, anxiety disorders, and sensory processing disorders, all of which involve difficulties filtering irrelevant stimuli and sustaining focus. This overlap suggests shared underlying mechanisms and positions misophonia within a broader transdiagnostic framework, where treatments targeting attentional control in other disorders may hold promise for alleviating misophonia-related difficulties.

Implications for existing Misophonia models

Although the goal of this study was not to test a specific model of misophonia, it is worth exploring how the results of this study align with existing models to varying degrees. Starting with the neurobiological model of misophonia proposed by Kumar and colleagues, which suggests that heightened distress in Misophonia arises from aberrant salience attribution and atypical interoception associated with dysfunction of the anterior insular cortex (AIC) (Kumar et al., 2017). This distress may be further amplified by hyperactivity in oral–facial motor regions, which in turn modulate AIC activity (Kumar et al., 2021). Additionally, social and cognitive appraisals, such as judgments about intentionality, perceived control, and moral blame, can intensify the emotional response (Berger et al., 2024). The results of my project are consistent with certain aspects of this model, specifically the trigger condition-specific reduction in matching precision observed in the misophonia group. This finding aligns with the notion that abnormal salience is attributed to trigger sounds, as evidenced by heightened AIC activation during trigger exposure in misophonics (Kumar et al., 2017). In addition, although the EEG results were not trigger-specific, the global reduction of Fz alpha power in the misophonia group may reflect a baseline weakness in attentional control that primes the system for the exaggerated salience responses predicted by the Kumar model when personally relevant triggers occur.

The neurophysiological model of misophonia proposed by Jastreboff and Jastreboff (2023) posits that the condition arises from subconscious conditioned reflexes linking the auditory system with the limbic and autonomic nervous systems. Central to this model is the claim that the auditory system itself remains functionally intact, and that treatment should focus on extinguishing maladaptive conditioned reflexes. The results of the present study are partially consistent with this framework. Specifically, the finding that trigger sounds did not impair pitch-matching accuracy supports the model's assertion that perceptual distortions do not drive misophonic responses. However, the observed trigger-specific reductions in response precision, together with alpha suppression at Fz that was specific to the misophonia group but not to trigger sounds, fall outside the scope of the model, which emphasizes emotional and autonomic reactivity rather than cognitive disruption. These findings suggest alterations in general working memory and selective attention mechanisms, rather than reflecting differences in the basic functionality of the auditory system. These results do not contradict the model but suggest a possible extension, in which conditioned reflexes may also interfere with higher-order cognitive systems involved in attentional regulation and working memory maintenance.

Lastly, the Mitchell-Dozier model of misophonia builds on Dozier's earlier behavioral model of misophonia as a classically conditioned response (Dozier et al., 2020), incorporating a cognitive-behavioral framework. This model defines misophonia as a five-phase disorder driven by classically conditioned physical reflexes to sensory stimuli, leading to emotional reactivity, maladaptive coping, and reinforcing environmental feedback (Dozier & Mitchell, 2022). In the context of this project, the observed reduction in working memory precision, without a corresponding drop in accuracy, among misophonic participants during exposure to trigger sounds aligns with Phase 3 of the Mitchell-Dozier model. This phase centers on the intense emotional and physiological reactivity that follows the conditioned reflex, and it maps directly onto the framework of emotion as an extraneous cognitive load introduced earlier in this paper. The reduction in working memory precision observed in misophonic participants during trigger trials is consistent with the notion that emotional arousal, characteristic of Phase 3, imposes additional cognitive burden, disrupting attentional stability and degrading the fidelity of memory representations. (Plass & Kalyuga, 2019).

Limitations

Several limitations should be considered when interpreting the findings of this study. First, while participants were screened for hyperacusis and gross hearing abnormalities, formal clinical interviews were not conducted, meaning that undiagnosed comorbidities (e.g., anxiety or attentional disorders) could have influenced group differences. Future work should seek to replicate and expand upon these findings using more ecologically valid tasks and more clinically diverse samples. For the EEG, the analyses were intentionally exploratory and did not rely on specific a priori hypotheses regarding electrode sites or time-frequency windows. While this approach allows for the discovery of potentially novel neural patterns, it also increases the risk of false positives and limits the interpretability of localized effects. Replication with more targeted hypotheses and confirmatory analyses will be essential to clarify the reliability and functional significance of the observed neural dynamics. To my knowledge, this is the most comprehensive EEG study of misophonia responses to trigger stimuli to date, providing a foundation for future confirmatory research on the topic and its observed effects.

Another area of limitation involves the task used in this project. Although the pitch-matching task provides a controlled and sensitive measure of auditory working memory, it may not fully capture the complexity of cognitive disruptions experienced by Misophonics in real-world environments. For instance, verbal communication often takes place in environments where misophonic triggers are common, such as during meals. Given that pitch information can be processed independently from verbal content (Deutsch, 1970), performance on the pitch-based task used in this study may not fully generalize to more ecologically valid situations, such as holding a conversation while exposed to trigger sounds.

Continuing with the issue of ecological validity, a significant limitation arises from the use of auditory-only trigger stimuli. In real-world contexts, trigger sounds are rarely experienced in isolation from other sensory cues. In fact, even the mere sight of a trigger source, such as seeing someone chewing gum from a distance, can be enough to provoke misophonia symptoms (Cervin et al., 2023; Jager et al., 2020). Moreover, co-occurring visual stimuli can modulate the misophonic response, as evidenced by reduced symptom severity when trigger sounds are paired with neutral visual cues (Samermit et al., 2022). While I chose to isolate the auditory aspect of misophonia triggers in this project to simplify interpretation of the EEG results, this choice may also limit the generalizability of the findings to real-world settings. Another consideration is the method used to edit stimuli for maximum identifiability. Because the correct identification of a trigger source is a key moderator of the misophonia response (Heller & Smith, 2022; Samermit et al., 2022), I edited the distractor clips to be as identifiable as possible based on my perception during the editing process. However, without verifying whether participants could accurately identify each source, some self-assessment manikin ratings may reflect general aversion to the sound's acoustic properties rather than a true misophonia response. Future studies should include verification of stimulus identification.

Another notable limitation is the absence of a generally aversive category of distractors. While not rising to the level of misophonic impairment, the sounds typical of misophonia tend to be generally aversive to some extent. Additionally, the trigger condition stimuli selected for control participants still exhibited aversive features, as indicated by the manikin scores, regardless of whether the aversion was misophonic in nature. This leaves open the possibility that at least part of any trigger-specific effects that could have been found for the misophonia group is explained by a general hypersensitivity to generally aversive sounds, rather than strictly the result of misophonia triggers. Future studies should examine this possibility by including a fourth condition with generally aversive sounds unrelated to misophonia.

There are also several limitations related to individual subject variables. First, as is common in psychology research, the sample consisted primarily of college students and therefore may not generalize to the wider population. Second, and more critically, the study did not account for participants' state or trait anxiety. The substantial difference in task performance between the misophonia and control groups, regardless of trial condition, suggests the possibility of an unmeasured characteristic specific to the misophonia group. Stress is known to reduce working memory capacity (Plass & Kalyuga, 2019), and it is reasonable to assume that individuals with misophonia experience higher stress levels than the general population, given the frequency of potential triggers. Indeed, misophonics are well documented to have elevated anxiety compared to the general population (for review, see Ferrer-Torres & Giménez-Llort, 2022), a factor likely amplified for participants entering a study in which they know they will be exposed to trigger sounds, particularly those who had completed the ranking task on the first day. Future studies would benefit from including assessments of state and trait anxiety to evaluate their potential impact on task performance.

Future directions

Future studies would benefit from several modifications to the procedures described in this project. Firstly, the incorporation of clinical interviews would allow for greater control of possible confounding comorbidities in misophonia. Controlling for these confounding effects can take several forms, including the exclusion of participants with confounding conditions, including the presence of these conditions as a variable in any analysis, or comparing the results of a subgroup of participants with specific comorbidities to those without these comorbidities to assess their effect. Additionally, since one of the core ideas of this project is that the negative emotions associated with misophonia function as extraneous cognitive load, future studies could include measures of state and trait anxiety or negative affect. Incorporating these assessments would allow researchers to account for individual differences in negative affect or anxiety that are unrelated to the task itself, providing a clearer picture of the specific impact of misophonia.

Another important direction for future research is to examine the feasibility of using the methods described in this dissertation to assess clinical interventions for misophonia. Current clinical trials for treatments of misophonia primarily rely on self-reported symptom severity as the outcome measure, which, although valuable, is susceptible to response biases (Hansen et al., 2021). In contrast, a task like the one presented here could provide a more reliable and objective means of evaluating treatment outcomes. For example, by establishing a patient's baseline performance on the task across various conditions and conducting reassessments at different stages of treatment, researchers could gain more robust insights into the effectiveness of these interventions.

Another methodological recommendation would be to incorporate multisensory stimuli. As noted in the limitations, misophonia is often accompanied by concurrent visual cues, such as seeing the source of the sound. Including a visual component, for example a video of the trigger source, could substantially improve the ecological validity of the experimental stimuli by more closely approximating real-world trigger encounters. Building on this idea, future work could also include alternative working memory tasks to examine whether the observed effects generalize beyond the current paradigm. In particular, adding a continuous visual working memory task alongside audio-visual stimuli would help determine whether the effects are domain-general or specific to the auditory modality. Additionally, incorporating a measure of selective attention, whether through a standardized assessment or a dedicated experimental task, would provide a more direct test of the attentional control deficits suggested by the current findings. This could enhance our understanding of how misophonia-related attentional disruptions affect cognitive performance across various contexts.

Furthermore, ecological validity could be enhanced by linking task performance to an incentive. In real-life trigger situations, there is often a motivating factor that compels individuals to remain engaged despite discomfort, for example, an office worker tolerating a triggering colleague in order to earn a paycheck. Incorporating a similar element into the task, such as informing participants that their performance will determine eligibility for different rewards based on a point system, could provide valuable insight into how cost–benefit considerations shape the misophonic experience in everyday contexts.

In addition to increasing ecological validity, it is also important to establish the methodological robustness of the task. A critical step toward assessing the feasibility of this approach is to first establish the intra-subject variability in task performance. In the current dissertation, all task data were collected from a single session. While group-level comparisons should be resistant to session-to-session variability, there may be significant individual variability in task performance that is unrelated to the trial conditions. Specifically, factors such as increased performance due to repeated task exposure (e.g., perceptual learning) or session-level variables (e.g., non-task-related distractions and personal issues) could cause an individual's performance to vary for reasons unrelated to treatment success (Dosher & Lu, 2024). Therefore, the first step in using this task as an outcome measure for interventions is to experimentally verify its reliability. Suppose differences in performance across conditions (silent vs. neutral vs. trigger) are found to be relatively consistent. In that case, a stronger case can be made that changes in performance throughout treatment reflect real changes in an individual’s cognitive function. One fairly straightforward method of assessing the stability of task performance over time would be a simple longitudinal design, where the methods employed here are repeated over several days. Analysis using trial number and/or trial day as a predictor could verify whether there are significant changes throughout the course of repeated testing.

Another promising avenue for future research using the methods described in this dissertation is to evaluate the effectiveness of common coping mechanisms employed by individuals with misophonia. Strategies such as wearing earplugs or using in-ear noise generators (e.g., headphones) to mask trigger sounds, as well as vocal mimicry, are frequently reported by Misophonics as helpful in real-world settings (Taylor, 2017). However, to date, there has been little empirical investigation into whether these strategies provide measurable relief, particularly in terms of mitigating the cognitive impact of trigger exposure. A straightforward approach would involve adapting the current experimental paradigm to allow participants to use these coping tools during the task, for example, by applying a digital filter to simulate the acoustic damping effect of earplugs (Wisniewski & Chuwonganant, 2025) or instructing participants to mimic the trigger sound upon hearing a warning cue. Comparing performance on trials with and without these aids using between-subjects, within-subjects, or mixed design, could reveal whether these strategies genuinely buffer against the attentional and memory disruptions caused by misophonic triggers.

An additional avenue for future research would be to examine how task performance changes over extended periods of exposure to triggers. In the current study, trigger sounds were presented in relatively short blocks interspersed with other conditions, making it unlikely that misophonia-related fatigue or cumulative effects significantly influenced performance. However, in real-world contexts, individuals with misophonia often endure prolonged exposure for example, sitting next to a gum-chewing classmate during a one-hour lecture. Replicating the current paradigm with varied block lengths and including intra-block trial number as a predictor could reveal how the impact of triggers evolves over time within a session. Such a design could help determine whether performance declines due to sensitization or improves due to habituation, offering valuable insight into the temporal dynamics and mechanisms of misophonic responses. Additionally, these effects could be assessed physiologically using the EEG paradigm established in this dissertation, even without the use of the behavioral task. Specifically, one would predict increased EEG effects if sensitization occurs, and reduced effects if habituation occurs.

Conclusion

In sum, this dissertation represents the first comprehensive effort to empirically assess the cognitive consequences of misophonic trigger exposure using both behavioral and EEG measures. By combining individualized stimulus selection, a continuous pitch-matching working memory task, and time-sensitive neural recordings, this work demonstrates that misophonic individuals experience measurable disruptions to working memory fidelity and exhibit distinct neural signatures of impaired attentional control. While effects were not always specific to trigger stimuli, the overall pattern suggests that misophonia is associated with heightened vulnerability to distraction and reduced capacity for cognitive inhibition. These findings lay the groundwork for future research aimed at clarifying the mechanisms of misophonia, developing ecologically valid assessments, and evaluating intervention strategies with objective performance-based measures.

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Appendix A - Pilot data

Oddball Pilot

The first idea we had for the physiological measure of misophonia was to look at the P300 ERP . the P300 is an ERP that occurs roughly 300 ms post stimulus onset, whose magnitude is proportional to the memorability of events. P300 latencies are thought to be negatively correlated with the speed of mental functions, such that longer latencies indicate cognitive performance (Polich, 2007). This component is typically assessed with the oddball paradigm, where frequently presented target (aka oddball) stimuli are displayed intermittently amongst more common "standard stimuli. For instance, having one high pitch tone play in the middle of a sequence of low pitch tones. Commonly, participants are tasked with doing something when they perceive a target, such as hitting a button (Donchin, 1981). There is anther version of this task where a third "distractor" task is also intermixed in the stimulus sequence, and it is this method we wanted to apply to our original project (Polich, 2007).

The idea at this point was that Misophonics should show greater P300 latencies when presented with a misophonia trigger as a distractor, compared to a neutral sound. The goal of this pilot was to see if this prediction held behaviorally, as indicated by Reaction times to pressing a button when shown the target, before collecting the EEG data. As such, we predicted significantly greater reaction times w the last distractor was a trigger for the misophonia group, compared to when the distractor was a neutral sound, and no difference between the distractors for the control group.

Oddball Pilot Methods

37 undergraduate students were recruited for this pilot and included in the analysis. Participants were assigned to groups (control vs Misophonic) based on the same criteria as in the primary study. Standard tones consisted of 0.5-second-long pure tones at 600 Hz, with the oddball tone set as a 0.5 second 800Hz tone. Distractors were sourced from the same audio files

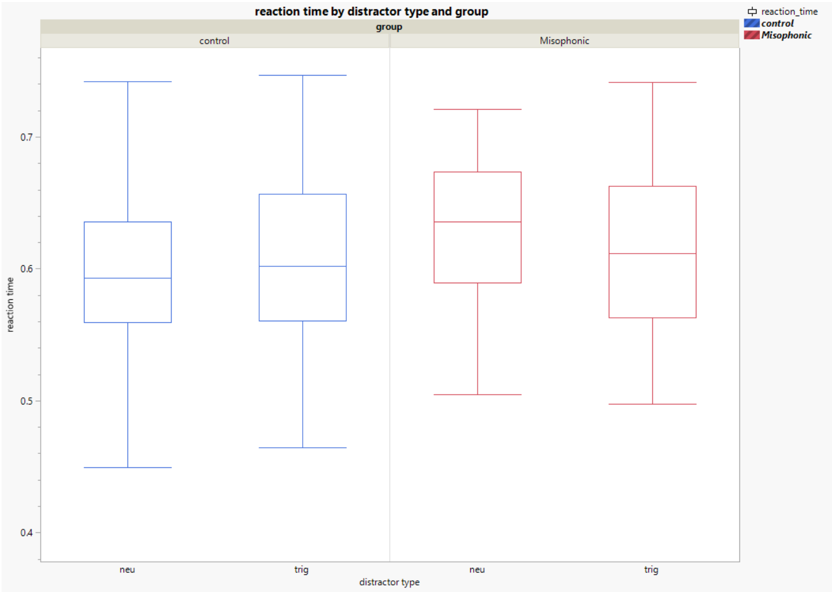
eventually used in the full dissertation document but clipped down to 0.5 second segments. Ther where 10 blocks, each consisting of 150 tone displays. In each block, 70% of the tones were the standard tone, 10% where distractor sounds, and 20% where the target (oddball) sounds. The nature of the distractors was based on block (neutral vs trigger blocks) with block type presented randomly across participants. Within each block, a random segment from the relevant sound bank was played for each distractor. The goal was to press the spacebar when the participant heard the target tone. See figure "A.1." for a visual.

Appendix Figure A.1. Oddball Pilot Paradigm

Oddball Pilot Results

Comparing the reaction times for the two groups across conditions found no significant differences. See figure A.2 and table A.1 for details.

Appendix Figure A.2 Oddball pilot Results



Appendix Table A.1 Oddball Pilot fixed Effects Tests

Source	Nparm	DFNum	DFDen	F Ratio	Prob > F
group	1	1	20.7	0.6092325	0.4439
group* distractor type	1	1	1095.7	3.872492	0.0493*
distractor type	1	1	1095.7	0.1592306	0.6899

Pitch Matching Pilot

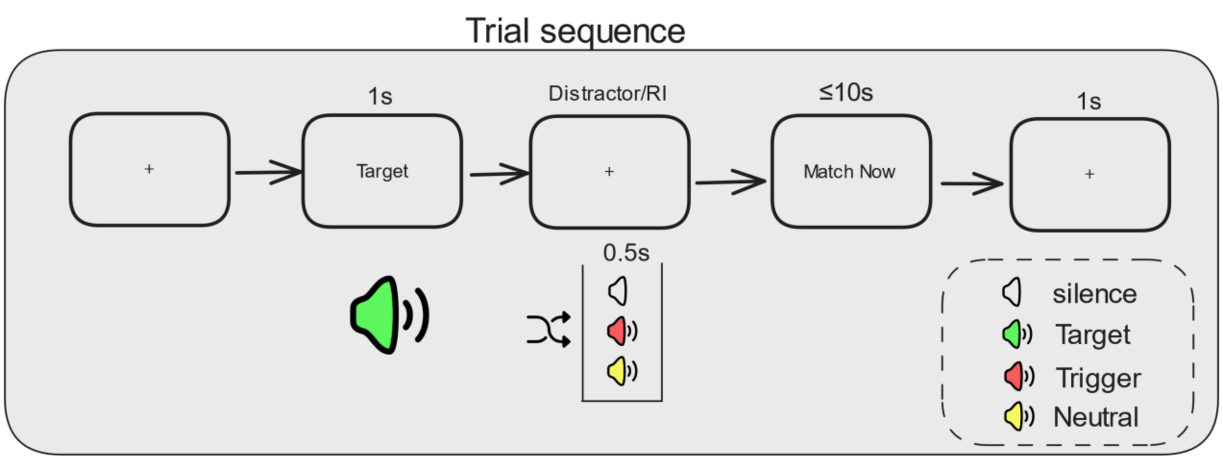
This pilot was a follow up to the oddball pilot. The goals and background were the same, and the rational for the task used is explained in the primary dissertation document. I predicted that individuals scoring high on the misophonia assessment would show greater disruption in the pitch matching task than those scoring lower.

Pitch Matching Pilot Methods

We recruited 66 undergraduates from Kansas State University. Target stimuli consisted of pure tones ranging from 500-800Hz. The task consisted of a simplified version of the task described in the primary dissertation document. Specifically, this task The task involved matching the sound of a target stimulus using a touchpad. Participants would hear a randomly generated pure tone, followed by a pause, and then reproduce the sound by moving their hand along the x-axis on the touchpad. This movement would change the pitch, and they would lock in their answer by pressing a button. The principal measurement was the accuracy of participants' adjustments, illustrated in a figure using example data from a single participant. A regression model was fit for each participant under different conditions: silent, misophonia trigger, and neutral environmental sounds.

Participants would see the word "target," hear the target sound, and then experience a retention interval that could be silent, filled with a trigger, or neutral sound. They had 10 seconds to make their responses. The accuracy was derived in the same manner as in the primary document.

Appendix Figure A.3. Pitch Matching Task Procedure

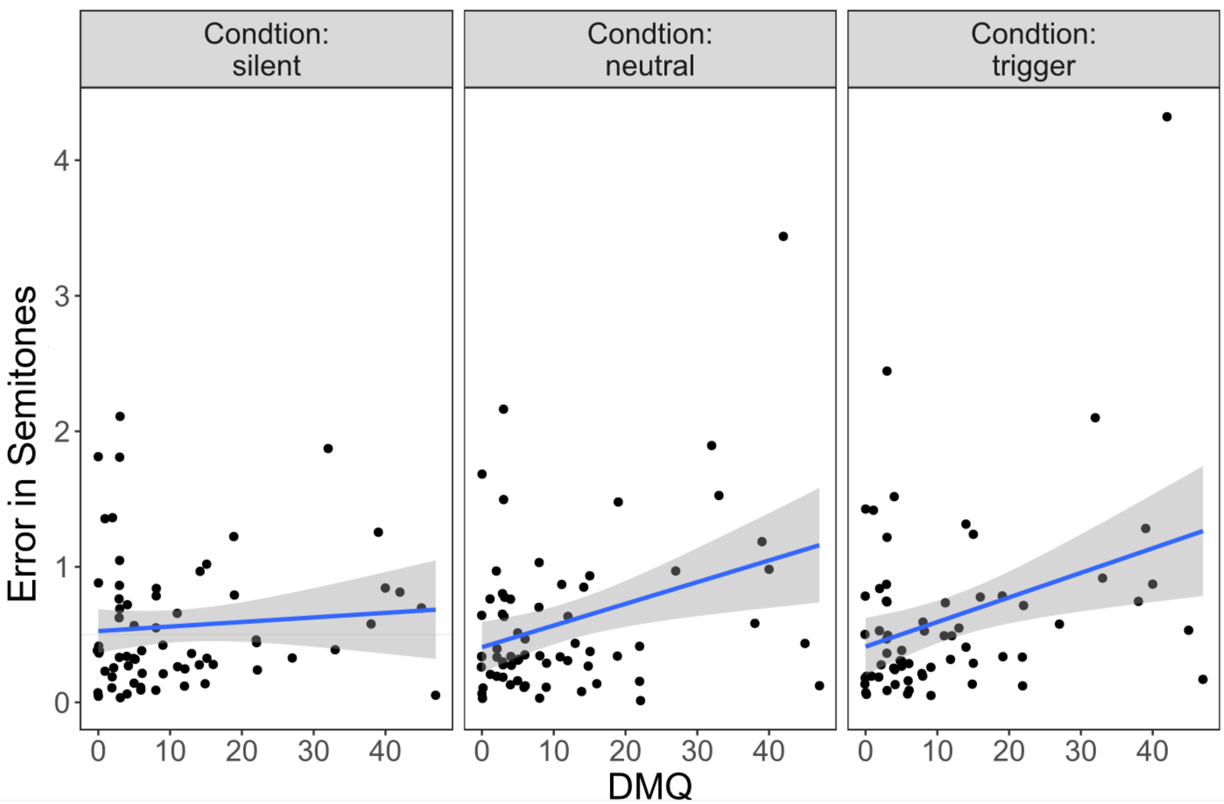


Pitch Matching Pilot Results

We did not find a specific effect of misophonia triggers. Participants, regardless of their misophonia score, did not perform worse in the trigger condition compared to the neutral condition. We believe this may be the result of technical issues leading to excessive response times compounded by the inclusion of participants how may have had general sound sensitives (ex: hyperacusis) unrelated to misophonia.

However, We did find DMQ score to significantly predict the performance in either distractor condition vs silent condition, suggesting an misophonia specific vulnerability to distraction, regardless of if the distractor is a misophonia trigger. This suggests some impact of misophonia on ongoing cognition and warrants further investigation in future studies. See Figure A.3 and table A.1 for more details on the results.

Appendix Figure A.4. Accuracy by DMQ Score By Condition



Appendix Table A.2. Pitch matching pilot Fixed Effects

Effect	Estimate	SE	95% CI Lower	95% CI Upper	df	t	p
(Intercept)	0.518	0.092	0.338	0.699	80.3	5.64	< .001
DMQ	-0.002	0.007	-0.016	0.012	29.4	-0.29	0.773
Neutral – Silent	-0.119	0.067	-0.251	0.013	128.0	-1.76	0.081
Trigger – Silent	-0.114	0.067	-0.246	0.018	128.0	-1.69	0.093
DMQ✻ Neutral – Silent	0.013	0.004	0.005	0.021	128.0	3.13	0.002
DMQ ✻ Trigger – Silent	0.015	0.004	0.007	0.023	128.0	3.66	< .001